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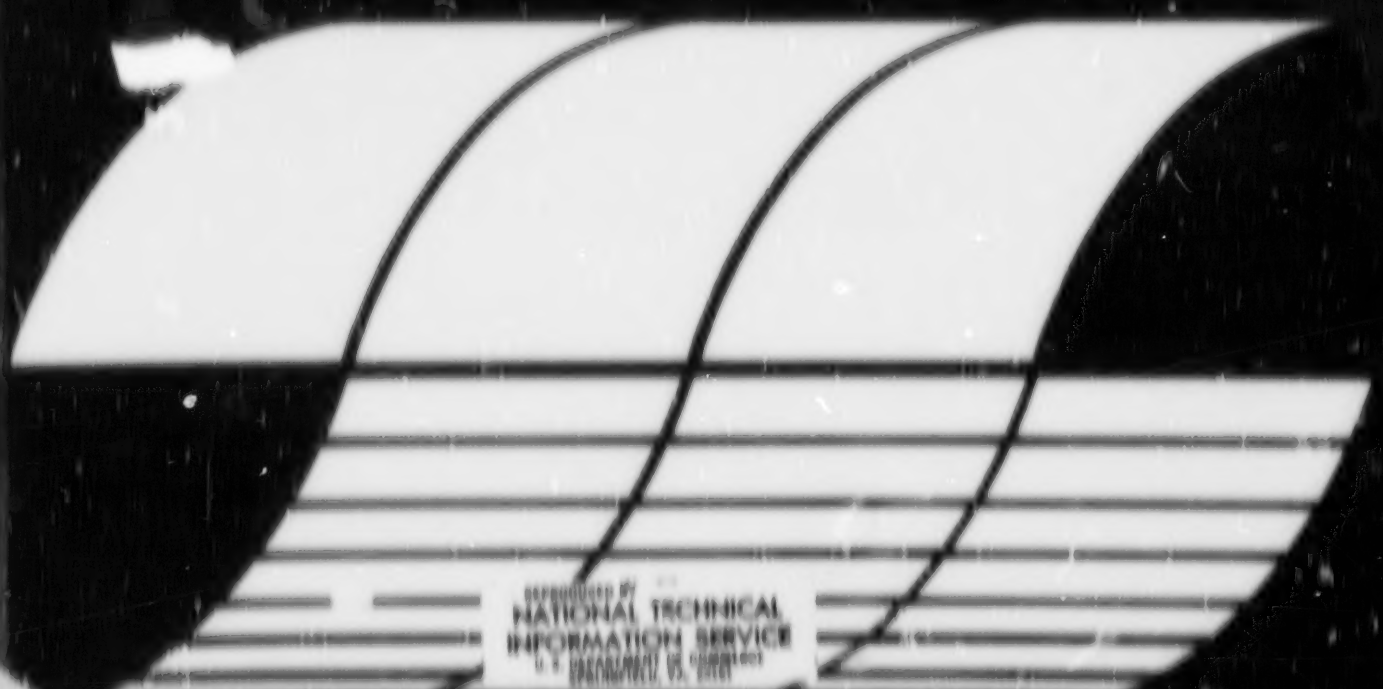

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SOURCE ASSESSMENT DOCUMENT

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory-Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report is an assessment of what is known about air and water emission from existing systems for converting waste to energy. The information contained herein will be of interest to those working with waste-to-energy systems, either as developers or operators. Request for further information concerning emission from waste-to-fuel systems should be directed to the Fuel Technology Branch, IERL-Ci.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

This report was prepared for the Industrial Environmental Research Laboratory-Cincinnati under EPA Contract No. 68-02-2166, Environmental Assessment of Waste to Energy Processes.

The program has the overall objective of identifying environmental impacts which might result from waste-to-energy conversion processes. These processes are categorized, on a generic basis, as: (a) waterwall incinerators; (b) combined firing systems; (c) thermochemical (pyrolysis) processes; (d) hog-fuel boilers; (e) biochemical systems; and (f) advanced combustion systems such as the CPU 400.

This source assessment document is the first publication on the subject program and it is intended to present what is currently known on emissions and emission control techniques in waste-to-energy conversion systems. This report discusses constituents in solid waste primarily with the idea of illustrating the diverse nature of the feedstock used in such systems. Also presented is an environmental impact analysis based on the contribution of each waste-to-energy conversion system to criteria and other major pollutants. Where emission data were lacking, engineering judgment was used to identify probable levels. A simplified methodology for a preliminary environmental assessment is illustrated. An overview of each of the waste-to-energy conversion systems including their pollution potential and applicable control technology is also contained in this document. The status of such systems as well as their locations, capacities and processing steps involved is identified, to the extent possible.

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SECTION 1

INTRODUCTION

Increased emphasis on conservation of energy and nonrenewable metal and mineral resources plus the growing unacceptability of traditional techniques for waste disposal have created the need for a critical evaluation of waste-to-energy conversion systems. Environmental insults that might result from waste conversion processes must not be overlooked. The object of this contract is to evaluate waste-to-energy conversion systems with respect to their degree of development, pollutant potential, and resulting impacts.

This source assessment document is the first publication on the subject contract, and it is intended to discuss what is currently known regarding environmental emissions from waste conversion systems. The report presents a brief discussion on the constituents of solid waste, an environmental impact analysis to identify expected emissions from waste conversion processes, an overview of waste-to-energy conversion systems (including their degree of development, pollutants emitted, and control techniques used), and a status summary on existing and proposed systems.

As part of the contract, several systems will be tested to monitor and analyze emissions, some of which may be potentially hazardous. The test program is currently underway, and separate reports for each system tested will become available upon completion. This source assessment document will be updated on an annual basis.

SECTION 2

SOLID WASTE CONSTITUENTS

Environmental assessment of waste-to-energy conversion systems can be simplified if the composition of the waste or "fuel" and the operating parameters of the process are known. In many cases, information on the process is well documented, but only limited reliable information is available on the waste itself because of wide variations in the composition. Variations may be a result of different geographic regions in which the waste was generated, seasonal differences, or different analytical methods used in the analysis of the refuse samples.

Concern is increasing that trace elements and organic constituents present in refuse can result in their emission into the environment during the waste-to-energy conversion process. Recently it was reported[1] that analytical studies are being conducted at the Bureau of Mines in Maryland to determine the concentration of major, minor, and trace elements in the combustible fractions of urban refuse. The following list contains representative elements known to be present in refuse. The same elements were also found in refuse samples analyzed in the St. Louis study.[2]

Major Elements (1,000 to 100,000 $\mu g/g$)	Minor Elements (0.1 to 999 $\mu g/g$)	
Aluminum	Antimony	Manganese
Calcium	Arsenic	Mercury
Chlorine	Barium	Molybdenum
Iron	Beryllium	Nickel
Magnesium	Bismuth	Niobium
Phosphorus	Boron	Platinum
Potassium	Cadmium	Rubidium
Silicon	Cesium	Selenium
Sodium	Chromium	Silver
Sulfur	Cobalt	Strontium
Titanium	Copper	Tantalum
Zinc	Germanium	Tin
	Gold	Tungsten
	Lead	Vanadium
	Lithium	Zirconium

Of these elements, several were found to be present in higher concentrations in refuse-derived fuel (RDF) than in coal.[3] These are listed as follows:

Antimony	Mercury
Barium	Nickel
Bismuth	Phosphorus
Cadmium	Silver
Chromium	Sodium
Copper	Tin
Lead	Titanium
Lithium	Tungsten
	Zinc

Many of the elements listed are potentially hazardous, indicating that RDF is not a clean fuel. To date, there are no measured data on the organic compounds present in refuse. When these data become available, it is likely that the number of potentially hazardous materials will increase significantly.

SECTION 3

ENVIRONMENTAL IMPACT ANALYSIS

The environmental impacts of waste-to-energy conversion systems can be evaluated on the basis of their contribution to each of the criteria and other major pollutants. This information is currently unavailable. However, based on the constituents in solid waste and an engineering analysis of the waste conversion process, some comments can be made on expected emissions from such systems. This section discusses emission contributions with respect to each criteria pollutant and then presents a general methodology that can be used for environmental impact assessment where only limited data are available.

CRITERIA POLLUTANTS

Particulate

Uncontrolled particulate emissions from waste conversion systems such as waterwall incinerators usually range from 2517.17 mg/nm^3 to 2974.84 mg/nm^3.[5] Recent emission tests conducted at the Nashville thermal transfer waterwall incinerator show uncontrolled grain loadings varying from 2153.33 to 3837.55 mg/nm^3, resulting in an average value of 3,746 mg/nm^3 for three runs at 12% CO_2.[6] Outlet grain loadings (controlled by an electrostatic precipitator) varied from 41.19 to 64.07 mg/nm^3, with a three-run average of 54.92 mg/nm^3 at 12% CO_2.[6] Uncontrolled grain loadings reported here are comparable to those from a recently tested coal-fired power plant that ranged from 3203.68 to 5492.02 mg/nm^3.[5]

Particulate emissions may be comparable between coal combustion and waterwall incineration on a grain loading basis. But information on potentially hazardous trace element emissions from waterwall incinerators is too limited to make such comparisons.

Trace elements such as arsenic, beryllium, mercury, silver, cadmium, copper, tin, etc., are reported to be present in fly ash from coal and from coal + RDF systems. However, no detailed sampling and analysis have been conducted to determine concentrations of such pollutants from waterwall incinerators using refuse as fuel. In addition, no information is available to

determine the enrichment, or preferential concentration, of potentially hazardous substances in the fine particulate fraction. One would anticipate that enrichment would occur in these systems in a manner similar to that reported by Gordon et al.[6] for regular municipal incinerators.

Combined firing systems using coal and RDF emit particulates at the rate of 4599.56 to 4897.05 mg/nm^3 without emission controls.[3] With electrostatic precipitator control, the values range from 183.07 to 228.83 mg/nm^3.[3] Reference 3 also indicates that fly ash from coal-only tests is higher in iron content but lower in lead, zinc, and chromium than is coal/RDF fly ash. Changes in trace element composition of the fly ash were also noted when coal and RDF were fired in the boiler. Combined firing caused an increase in the concentration of antimony, arsenic, barium, cadmium, chromium, copper, lead, mercury, zinc, bromine, and chlorine in the fly ash.[3]

Particulate emissions from boilers using wood waste as fuel can vary depending on the extent of char reinjection, boiler type, excess air used, wood waste type, and wood moisture content. A typical particulate emission factor (uncontrolled) for a wood-fired boiler is reported to be 12.5 to 15 g/kg of wood without fly ash reinjection. For boilers with reinjection, the uncontrolled emission factor is reported to be 15 to 17.5 g/kg.

Particle size information for emissions from municipal incinerators and a coal/RDF-fired system is given in Table 1 and Figure 1, respectively. These illustrations show that fly ash from incinerators is much finer than that from a coal/RDF system, with 13% to 30% by weight less than 1 μm in diameter.

Particulate emission rate and particle size data for other waste-to-energy conversion systems such as pyrolysis, biochemical systems, and advanced combustion processes like the CPU-400 are meager. But particulate emissions from these systems should be much lower than those from other waste conversion systems discussed above, namely, incinerators and combined fired systems.

SO_2

SO_2 emissions from waste-to-energy conversion systems are not expected to be significant, since the concentration of sulfur in refuse is on the order of 0.14 g S/10^6 joule in contrast to 0.60 g S/10^6 joule in coal.[7]

Tests at the Nashville incinerator showed an average SO_2 concentration of 38 μl/liter.[7] Another study reports a range of 33 to 162 μl/liter.[8] These values are lower than would be expected with coal combustion. On the other hand, tests with RDF and coal in a combined-fired boiler did not show any reduction in SO_2 concentration when compared with coal-only tests.[3]

TABLE 1. PARTICLE SIZE DISTRIBUTION OF MUNICIPAL INCINERATOR FLY ASH[10]

Diameter (μm)	Wt % less than stated diameter	
	Study 1	Study 2
1,000	***	***
250	***	81
150	***	74
45	45	59
30	41	55
20	36	51
15	***	48
10	30	45
5	23	40
1	13	30

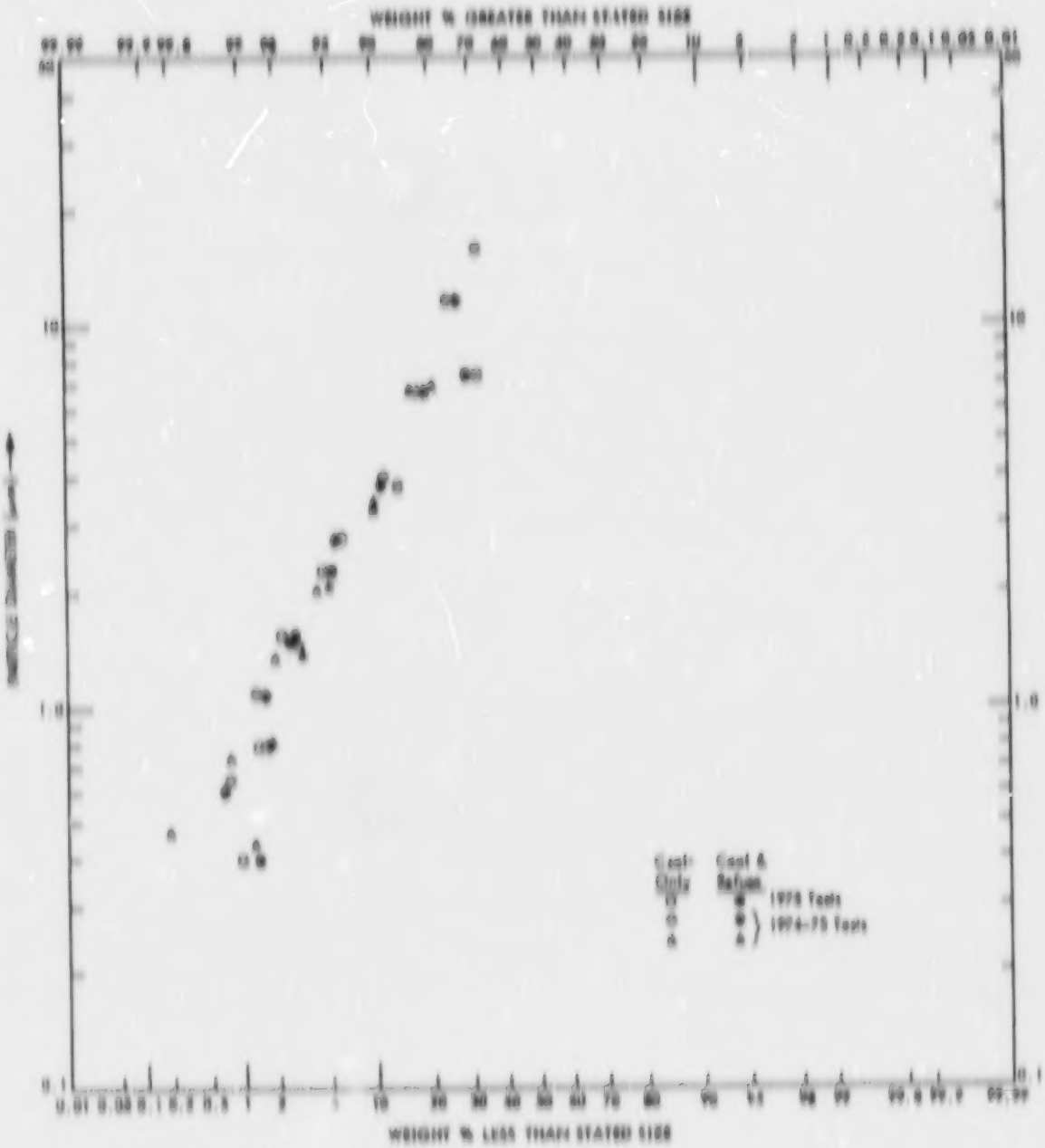

Figure 1. Average particle size data for uncontrolled emissions from coal-only and coal/RDF systems.

the reason could have been that only 10% RDF was used with coal. This interpretation is supported by another RDF/coal study in which 1:1 and 2:1 mixtures (by volume) of RDF and coal were utilized.[9] Jackson[9] indicates that the 1:1 mix had significantly lower SO_2 emission levels than coal.

SO_2 emissions from wood-waste boilers should be negligible, since the sulfur content of wood is about 0.1% by weight. For coal, the sulfur content can vary widely depending on the source of the coal.

Pyrolysis systems such as the Purox system do not report any SO_2 in the fuel gas.

NO_x

The concentration of NO_x from waterwall incinerators is reported to average 146 µl/liter.[7] For a coal/RDF system, the NO_x concentration was lower than that obtained during coal-only tests.[9] The NO_x emission factor for wood and bark combustion is reported to be 5 g/kg of wood.[11] Based on these limited data, NO_x does not appear to be a major pollutant of concern in waste-as-fuel systems.

CO

Carbon monoxide emissions from waterwall incinerators average 153 µl/liter.[7] For wood and bark combustion, the CO emission factor is 1 g/kg of wood.[11] For the coal/RDF-fired system, no noticeable differences were observed in CO concentrations when compared with CO emissions from coal-only tests.[2]

Hydrocarbons

Uncontrolled hydrocarbon emissions are reported to range from 0.4 to 42.5 µl/liter for municipal incinerators.[8] For a coal/RDF system, the hydrocarbon concentration was lower when coal and RDF were used in a 1:1 ratio by volume than when coal only was used.[9]

Pyrolysis systems will probably result in high hydrocarbon concentrations. The Purox system reports a methane concentration of 5% by volume in the fuel gas.[10] This should not be of concern, however, since the fuel gas is the product itself and hence is not expected to be emitted into the atmosphere before combustion.

METHODOLOGY FOR ENVIRONMENTAL ASSESSMENT

Generally, the adverse effects of pollutants are evaluated from the extent to which they are deemed health hazards. In determining the degree of hazard, some of the more important considerations include the emission rate of the pollutant, the number of other sources emitting the same pollutant and their emission rates, and atmospheric conditions governing the transport of the pollutant in question. In addition, establishing the critical dosage level based on health studies is a very significant factor.[13] For most pollutants and substances considered to be hazardous, allowable ambient concentrations or exposure limits have not been established.

There are several recent reports in the literature that discuss methods to estimate the impact of pollutants based on some sort of prioritization procedure.[14-16] For example, Simutus[14] describes a prioritization procedure for the rank-ordering of air pollution sources by computing a relative environmental impact factor for each of the sources investigated. The basic proposition of this prioritization model is that emission sources can be ranked based on the potential degree of hazard that they impose on individuals in their environment. This degree of hazard can be expressed in different ways. A traditional method of expressing degree of hazard has been to use the mass of emissions from various source types. Other techniques have used ambient air contributions of a given source type and the resulting degradation of ambient air quality as an indicator of source severity.

Simutus[15] has developed mathematical models to rank relatively the environmental impact of water and solid residue emissions using the air prioritization model[16] reported earlier. The water model is based on mass of emission, hazard potential of the emission, ambient water loading, and population density in the emission region.[15] Simutus[16] uses a simulated approach to compare the ground level concentration contribution of pollutants relative to some potentially hazardous concentrations of the same species.

A simplified summary of the source severity concept and how it can be utilized in the subject program is discussed in Appendix A.

SECTION 4

OVERVIEW OF WASTE-TO-ENERGY CONVERSION SYSTEMS

The major waste-to-energy systems, on a generic basis, are:

* Waterwall incinerators
* Combined firing systems
* Thermochemical processes (pyrolysis)
* Rdf-fuel boilers
* Biochemical systems
* Advanced combustion systems (CPU-400)

A brief description of each generic system including its pollution potential and applicable control technology is presented below and followed by a bibliographic list for each system.

WATERWALL INCINERATORS

System Description

Originally incinerators were designed to dispose of refuse and other unwanted combustibles by thermal decomposition. However, increasing emphasis on energy conservation has led to incorporation of heat recovery systems in most modern incinerators.

The use of raw refuse as a fuel for steam production in waterwall incinerators began in Europe and has now been technologically developed to a fine degree. The European design has generally served as the basis for a few recent U.S. installations, listed in Table 2.

Refuse is normally burned "as received" in a waterwall incinerator, with size reduction equipment only for oversize or bulky refuse. Firing is usually accomplished using traveling grates. Combustion gases exchange heat in the boiler section, superheater and economizer, thereby reducing flue gas to an exit temperature of approximately 93°C to 232°C. Flue gas exit temperatures and excess air levels are generally much higher than for suspension firing, and boiler efficiencies are proportionately lower than those found in electric utility boilers. Auxiliary fuels such as oil or coal are usually provided for supplementary steam generation.

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Pollution Potential

Pollutants from waterwall incinerators include particulates, gases, wastewater from ash sluicing, bottom ash, and captured fly ash. Recent tests[9] on the Nashville incinerator showed average inlet grain loadings of 2,746 mg/nm^3 and an average outlet loading of 54.92 mg/nm^3 after the electrostatic precipitator (ESP). Similar tests performed at other U.S. and foreign waterwall incinerators indicate that fly ash emissions range from approximately 0.066 to 0.63 g/10^6 joule of heat input, with the lower values (0.064 to 0.120 g/10^6 joule) representative of U.S. installations.[10]

Particle size data for fly ash particulates from municipal incinerators indicate that 30% to 45% by weight are less than 10 μm, 23% to 40% are less than 5 μm, and 13% to 30% are less than 1 μm.[10]

A more important environmental factor of fly ash particulates from waste incineration is the enrichment or preferential concentration of several trace elements in the smaller-sized portions. Gordon et al.[6] report enrichment factors from municipal incinerators of 1,000; 270; 18; and 10 for cadmium, lead, copper, and zinc, respectively. The same phenomenon is likely to occur in waterwall incinerators.

Gaseous emissions consist of SO_2, NO_x, chlorides, and CO in addition to CO_2, oxygen, and hydrocarbons. Table 3 summarizes the concentrations of these gases observed in tests conducted at Nashville.[9] Similar tests conducted at the municipal incinerator in Babylon, New York, showed NO_x concentrations ranging from 53 to 115 μl/liter.[12] The SO_2 and chloride concentrations at the same facility were observed to be 36 to 195 μl/liter and 214 to 1,230 μl/liter, respectively.[12] The differences in the gas concentrations could be a result of using different sampling and analysis methods and/or different incinerator operating characteristics.

In general, SO_2 emissions from incinerators will be lower than those observed from coal-fired power plants since refuse has a lower sulfur level. Chloride emissions can be high, since refuse can contain elevated quantities of plastics. These chloride emissions can create a significant problem; even though they can be easily scrubbed from the gas stream, their subsequent removal from the scrubbing water can result in water pollution.

Hydrocarbon emissions from municipal incinerators are reported to be in the range of 0.4 to 42.5 μl/liter.[6,12] Methane and ethylene appear to be the predominant species. C_1 through C_5 hydrocarbons may be listed as minor constituents of incinerator emission when combustion conditions are good.[12]

TABLE 3. ANALYSIS OF FLUE GAS FROM BLAST-FURNACE INCINERATOR[a]

Gas	Test number and date						
	1 2-13-73	2 2-13-73	3 2-13-73	4 2-14-73	5 2-14-73	6 2-15-73	Average
CO_2 (%)	10.0	9.8	11.4	10.8	10.3	10.3	10.4
O_2 (%)	10.5	10.3	8.5	9.0	9.3	9.6	9.5
Excess air (%)	102	100	69	73	79	83	84
NO_x µl/liter	107	130	177	150	165	134	146
SO_2 µl/liter	46	51	39	30	22	28	36
CO µl/liter	158	179	100	—	—	—	115
Chloride µl/liter	65	—	177	170	78	—	110

Relatively little information is available on water pollutants from waterwall incinerators. The only significant water usage, other than for steam generation, occurs in ash sluicing. Water quenching of ash from the boiler is usually necessary to break up clinkers and to quench burning materials. Thus water pollution problems occur and create the need for treatment facilities to be constructed as part of the incinerator plant. Other wastewater sources include the sanitary system's boiler blowdown, demineralizer backwash, and quench channel overflow. At Saugus, the average wastewater discharge is estimated to be approximately 0.0057 m^3/sec.[17] No information is available describing wastewater quality from the various waterwall incinerator plants.

Solid waste emissions from waterwall incinerators consist of bottom ash and captured fly ash. They can be disposed of in landfills.

Pollution Control Technology

Information presented here is primarily based on the Nashville and the Saugus systems. Data on other locations are not readily available. However, since the two systems discussed here are among the most recent facilities, the discussion is probably more representative of current control technology.

Nashville--

Air emissions from the Nashville incinerator have been controlled at various times using different types of wet scrubbers. The system now has an electrostatic precipitator that meets the local regulation, and a second electrostatic precipitator is in the process of being installed.

Recent test data[6] on the American Air Filter ESP unit operating at Nashville showed the following inlet/outlet particulate loadings when corrected for 12% CO_2.

Inlet (mg/m^3)	Outlet (mg/m^3)
2153.33	64.07
2219.69	41.19
3837.33	61.79
Average 2736.66	Average 55.68

The tests were conducted using U.S. Environmental Protection Agency (EPA) methods and were done only to determine particulate loadings at full load. No particle sizing or gas composition measurements were made.

Experience with scrubbers was reported[18] to be both frustrating and expensive. The original low-energy scrubbers were ineffective in collecting fine particulate. Stack sampling indicated that 90% of the particulate escaping the scrubber had an average diameter of less than 6 μm. Modifications to the original scrubbers increased the pressure drop and the collection efficiency, but not sufficiently to bring the units into compliance.

Pilot tests of two other wet collection devices (high pressure spray scrubber and high temperature water washing nozzle) indicated possible compliance. However, excessive steam usage and stringent recycle water cleanup requirements were factors that caused their rejection in favor of electrostatic precipitators.

A pilot baghouse program is being conducted in two phases. In the initial baghouse program, five fabrics of glass, stainless steel, and synthetic fibers were utilized in two baghouses, a pulse type and a backflow type. Meaningful stack sampling was not conducted, although visible emissions appeared to be well controlled. The five fabrics held up for the test period of approximately 3 months. Burst tests and other analyses of one of the fabrics (an aramid felt) indicated a projected total life expectancy of only 5 to 6 months. This result is not surprising because the fiber is not acid resistant.

The second-phase EPA-sponsored program on fabric filters is just getting under way at Nashville. An 84,95 m^3/min slip stream from the heat recovery incinerator is still being used as the gas source. Objectives of the current testing program are to:[18] (a) screen three types of high-temperature, acid-resistant filter media; (b) determine efficiency and optimum air-to-cloth ratios for the various filter media; (c) make technical economic comparisons of a baghouse using these media versus other particulate control methods such as ESP's and wet scrubbers; and (d) recommend a prime filter media candidate for followup life expectancy programs.

The bags to be tested are in various stages of commercial development. They include a microporous Teflon-type laminate, a woven glass fiber coated with Teflon, and a coated glass felt.

Solid waste at the Nashville facility primarily consists of captured fly ash and bottom ash. These materials could be disposed of in landfills. No information is apparently available on any wastewater treatment facility at Nashville. However, treatment of wastewater from this facility should not pose any control problems.

Saugus--

The Saugus system has two Wheelabrator-Lurgi electrostatic precipitators capable of handling 5796.1 m^3/min each at 220°C. They are designed to

control particulates to 57.21 mg/nm^3, corrected to 12% CO_2, and they are apparently operating satisfactorily under the Metropolitan Boston Air Pollution Control District requirement of 114.62 mg/nm^3 at 12% CO_2. No test data are available.

Wastewater sources are the sanitary system, boiler blowdown, demineralizer backwash, and quench channel overflow. All blowdown and backwash is neutralized as required and pumped to a holding tank that feeds the ash quench conveyor channels. No ash quench water is recirculated, since it is progressively removed in the wet ash with overflow to the sewer. Under operating conditions, total flow to the sewer is expected to consist primarily of the sanitary system discharge.[17]

The front ash discharge from the furnace and the mechanically conveyed ash from the boiler and precipitator hoppers are mechanically conveyed from a quench tank to a classifying house. In the house, the drag conveyor drops the ash into a trommel screen where it is classified into three fractions. Pieces larger than about 7.62 cm drop into a truck, and the ash that drops through the screen is further classified into magnetic and nonmagnetic fractions, each of which goes to a separate truck for sale to a steel plant and disposal, respectively.

Recommended Reading

For additional information on waterwall incinerators the following references are provided:

1. Astrom, L., F. Kranebitter, O. Strandell, and D. W. Harris, "Comparative Study of European and North American Steam Producing Incinerators," in Proceedings of 1976 National Incinerator Conference, Miami, Florida, May 1976.

2. Bump, R. L., "The Use of Electrostatic Precipitators on Municipal Incinerators in Recent Years," in Proceedings of 1976 National Waste Processing Conference, Boston, Massachusetts, May 1976.

3. Garotti, A. A., and R. R. Kaiser, "Concentrations of Twenty Gaseous Chemical Species in the Flue Gas of a Municipal Incinerator," JAPCA, 27(4), April 1977.

4. Gorrie, R. G. (ed.), Principles and Practices of Incineration, Wiley-Interscience, New York, 1969.

5. Roberts, R. M., R. T. Branham, R. G. Hanson, S. B. Kilner, R. E. Sommerlad, J. D. Shonker, R. W. Bryers, A. D. Konopka, J. McKenna, Systems Evaluation of Refuse as a Low Sulfur Fuel, Vol. I and II, Report to Environmental Protection Agency, Envirogenics Company, November 1971.

6. Schwieger, R. G., "Power from Waste," Special Report in Power, February 1975.

COMBINED FIRING SYSTEMS

System Description

Combined firing systems are those that use RDF with coal or oil for production of electric power in utility boilers.

Combined firing systems being planned for the United States generally utilize both materials and energy recovery. Figure 3 presents a simplified schematic for this type of systems. As shown in the figure, preconversion processing of the waste is required for enrichment of the waste to RDF. The preconversion processing also facilitates the recovery of ferrous and nonferrous metal and glass from the waste. RDF and a fossil fuel (coal or oil) can then be readily combusted to generate steam or electricity. A representative list of combined firing systems is given in Table 6.

On a smaller scale, particularly in industrial boilers, wood waste (wood chips) is commonly used with coal. In this case, there is usually no need for processing the waste. However, in systems where bark is used with coal, the bark must be shredded. Combined firing systems utilizing wood and coal are generally located in areas where there is an adequate supply of wood waste, and they are generally operated on a smaller scale than systems using RDF and coal or oil.

Pollution Potential

Combined firing systems can consist of coal and RDF, oil and RDF, coal and wood waste, and oil and wood waste. Where RDF is used, processing of municipal solid waste is required. Depending on the type of wood waste (wood chips or bark), processing may become necessary.

If processing of MSW or bark is undertaken, then the processing plant becomes the first emission source in the waste-to-energy conversion chain. MSW processing usually involves shredding, air classification, and removal of ferrous and sometimes aluminum metal. Pollution problems from such a facility can include residue to be disposed of and particulate pollutants from the air

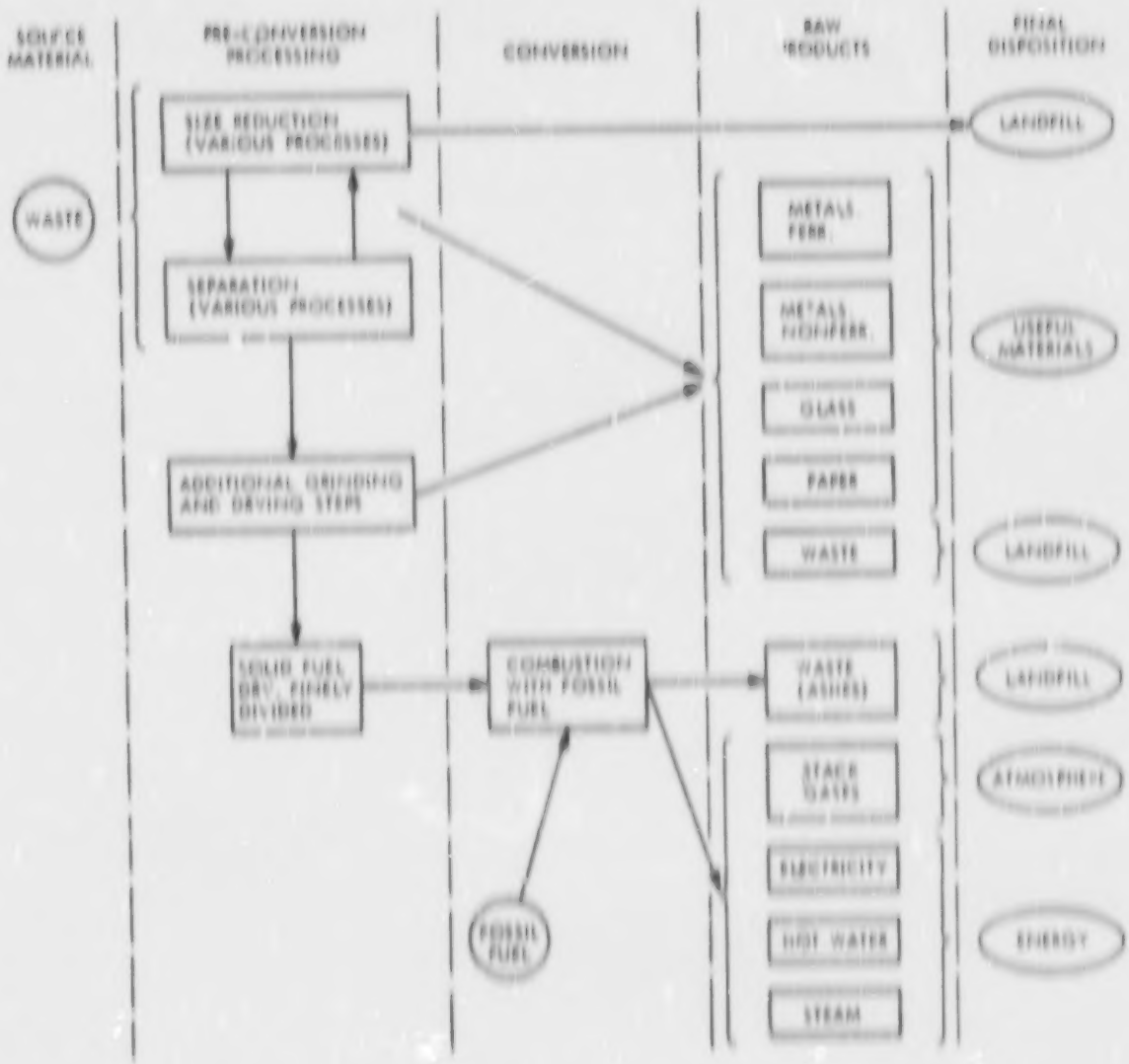

Figure 2. Schematic of combined firing system.

[illegible]

[illegible]	[illegible] capacity (tpd)	Processing steps[a] (tpd)	Products
[illegible], Iowa	[illegible]	[illegible]	[illegible]
[illegible], Illinois (Crawford)	[illegible]	[illegible]	[illegible]
[illegible], Massachusetts	[illegible]	[illegible]	[illegible]
[illegible], Virginia	[illegible]	[illegible]	[illegible]
[illegible], Missouri	[illegible]	[illegible]	[illegible]
[illegible], New York	[illegible]	[illegible]	[illegible]
[illegible], New York	[illegible]	[illegible]	[illegible]
[illegible], New York	[illegible]	[illegible]	[illegible]
[illegible], Delaware (New Castle County)	[illegible]	[illegible]	[illegible]
[illegible], Connecticut	[illegible]	[illegible]	[illegible]
[illegible], Massachusetts	[illegible]	[illegible]	[illegible]
[illegible], Wisconsin	[illegible]	[illegible]	[illegible]

[a] [illegible]

classifier control system. If washdown operations are involved, this will result in wastewater discharge. Bark processing will usually involve only particulate discharge. A detailed pollutant characterization of a MSW processing facility has been presented by Gorman.[2]

Among the combined firing systems cited above, detailed emission information exists only for the coal and RDF system.[2,9] Emissions from the power plant fired with coal and RDF included solids in the form of bottom ash and captured fly ash, air emissions in the form of particulates and gases, and boiler sluice water. The bottom ash accumulation rate averaged 67.98 kg/min for coal and RDF (at 5% to 10% RDF) in contrast to 10.07 kg/min for Orient 6 coal.[2] Also, elements such as lead, antimony, and tin are present in greater concentrations in fly ash collected by the ESP when coal and RDF are fired together than when coal alone is used. A similar trend appears for lead and chromium in bottom ash.[2]

Analysis of atmospheric emissions from the boiler fired with coal and RDF indicates that hazardous pollutants such as beryllium, cadmium, copper, lead, etc. are emitted in larger concentrations when RDF is fired with coal. Similarly, chloride emissions increase when RDF is fired with coal. Emissions of other gaseous pollutants such as CO, SO_2, NO_x, and HC were not significantly different when RDF was fired with coal.[2] One would expect the SO_2 concentration to decrease for coal and RDF, since refuse had a sulfur level of only 0.14 g/10^6 joule in contrast to Orient 6 coal, which has a sulfur level of 0.60 g/10^6 joule. [illegible] because only 10% of the feed constituted RDF in the study reported by Gorman et al.[2], the difference may not have been noticeable. This interpretation is supported by another RDF/coal study in which 1:1 and 2:1 mixes (by volume) of RDF and coal were utilized.[9] Jackson[9] indicates that the 1:1 mix had significantly lower SO_2, HC, and NO_x emission levels than coal. Particulate emissions were unchanged, and lead, chloride, and fluoride emissions were significantly increased with the 1:1 mix. Another important finding reported by Jackson[9] is that lead was found predominantly in the submicron-sized particle fraction. Particles in the stack effluent contained 265 times more lead than particles collected by a multiclone.[9]

Water effluent from a coal/RDF system is limited to sluice water. A comparison was made between pollutants contained in sluice water from such a system and from a system firing coal only.[2] There was no significant difference between the two sluice water samples in potentially hazardous pollutants such as antimony, arsenic, barium, beryllium, cadmium, chromium, copper, lead, mercury, selenium, titanium, vanadium, zinc, bromine, chlorine, and fluorine. However, total dissolved solids (TDS), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) were higher for sluice water from the coal/RDF system.

A decrease in the performance of the electrostatic precipitator was noted in the test program at St. Louis when RDF was substituted for coal.[3] The decrease in ESP efficiency was attributed to the 8% increase in gas flow rate and changes in fly ash and gas composition. These results suggest that similar problems may occur for other boiler/control equipment systems modified to fire RDF and coal.

Power plants fired with oil and RDF will most likely emit particulates (carbon and ash), NO_x, SO_x, and hydrocarbons. Based on the St. Louis/Union Electric combined firing demonstration of coal and refuse, it is thought that gaseous emissions of CO, CO_2, NO_x, and organics will be relatively unchanged in oil/RDF systems.

Table 5 presents comparative data on the air emission characteristics from oil- and coal-fired electric generating plants. Notable differences between these systems that affect collection efficiency include a smaller average particle size, a lower grain loading, and a higher carrier-gas flow rate for oil units. Evidence indicates that the size distribution of particulate from oil-fired systems is bimodal, with large, hollow carbonaceous particles and finer, condensed, spherical particulate and ash less than 1 μm. The size distribution depends on the degree of atomization of the oil, the efficiency of mixing, the number of collisions between fly ash particles, the flame temperature, the air-fuel ratio, the design of the firebox, and the flue gas path through the boiler to the stack. The lighter particles usually contain less carbon and are smaller.

Installed particulate emission controls designed for coal are predicted to be less efficient for the control of particulate emissions from combined firing of oil and RDF. Anticipated control difficulties result mostly from relatively high particulate loadings, high flue-gas volumes, fine particulates, relatively low particle density, and relatively high fractions of carbonaceous, low-resistivity particulates.

Emission data for combined firing systems using coal and wood waste and oil and wood waste were not available at Midwest Research Institute at the time this document was prepared. The use of wood waste as a supplementary fuel is not expected to markedly alter air emissions, but bottom ash generation rates will probably increase. Degradation in particulate control system performance may also occur.

The preceding discussion on co-fired systems indicates that the existing data base on environmental impacts is more extensive than for waterwall incinerators. The broad outlines of the environmental problems have been defined. Existing data indicate that the major adverse impacts of the combined firing systems are related to:

TABLE 5. [illegible] DATA FOR U.S. AND FOREIGN [illegible][a]

Electric utility power plants	Particulate			Gaseous pollutants	
	Particle size[b]	Mass loading[c]	Chemical composition[d]	Gas temperature (°F)	Chemical composition
Dual-fired	Typical distribution (pulverized coal): $E_1 < 45$, $E_2 < 15$, $E_3 < 15$, $E_4 < 5$ (particle size varies with type of coal)	457.82-11,653.36 (dependent on type of coal)	Fly ash SiO_2:17-45 Fe_2O_3:2-38 Al_2O_3:5-38 CaO:1.1-22 MgO:0.1-5 Na_2O:0.1-4	1,25-17,8 9,34-18,31	CO_2, O_2, N_2, SO_2, SO_3, and H_2O
Oil-fired	$E_1 < 1$	22.89-457.82	Carbon, ash, SiO_2, V_2O_5, Al_2O_3, sulfates, and a wide variety of minor components	43-11,400 348-780	CO_2, O_2, N_2, SO_2, SO_3, and H_2O

a. All data for noncoalfired sources.
b. Particle size data are presented as weight % less or greater than a specific diameter: $x > y$, $x < y$; x = weight %, y = particle size (microns).
c. kg/m^3.
d. Weight %.
e. Flow rate data are presented in thousands of normal cubic meters per minute.

--increased air emissions of some trace elements (e.g., antimony, beryllium, copper, lead, zinc, cadmium, and chlorine),

--increased bottom ash generation and associated disposal problems (i.e., leachate problems),

--increased levels of BOD, COD, and TDS in boiler sluice water, and

--apparent decrease in control system performance under conditions of combined firing.

Pollution Control Technology

Combined firing systems discussed here are restricted to RDF and coal and RDF and oil. No control technology information was available for systems fired with wood and coal or wood and oil.

RDF and Coal--

The St. Louis study[2] presents a comprehensive environmental evaluation of a coal/RDF system involving both the firing and processing facility.

Power plant.--Pollutant streams (from the coal/RDF-burning plant) for which controls are employed are:

- Air emissions from stack (particulates and gases),
- Solids (boiler bottom ash and fly ash), and
- Wastewater (boiler sluice water).

Air emissions at the St. Louis facility are controlled by an electrostatic precipitator. Particulate emission measurements showed that refuse firing did not apparently affect inlet grain loadings to the ESP.[2]

The firing of RDF did have an effect on ESP spark rate and power levels, coincident with losses in ESP collection efficiency at output loads above 100 (MW).

Specific factors analyzed as having a direct bearing on ESP performance were: (a) inlet particle size data; (b) particulate resistivity data; (c) particulate reentrainment; (d) electrical operating conditions for the ESP; and (e) gas-volume flow rates. The fractional efficiency of the ESP was also studied to see if the decreased efficiency could be related to specific ranges of particle sizes.

The analysis of ESP performance led to the following conclusions:[2]

1. ESP efficiency decreases with increasing gas-volume flow rate, both for coal-only and coal and RDF conditions.

2. Decreases in efficiency when burning coal and RDF as compared to coal are probably not attributable to changes in inlet particle size distribution, inlet grain loading, or reentrainment problems.

3. Decreases in ESP efficiency when burning coal and RDF as compared to coal are most likely due to the 8%-increased gas flow rate and to changes in the ash and gas properties that occur with the burning of RDF.

4. Changes in the fly ash properties that result from burning RDF probably cause small changes in particulate resistivity.

5. The small changes in resistivity caused by burning RDF are probably magnified in terms of their influence on ESP efficiency because measured resistivities are in a very critical range for the onset of back corona and other electrical problems.

6. The decreased overall ESP efficiency at high boiler loads primarily results from an increase in emissions of particles in the 1.0 to 10.0 μm size range.

There are several control alternatives that could be considered for particulate emissions. A list of such alternatives includes: (a) adding another control device (e.g., cyclone) before or after the ESP; (b) increasing the size of the ESP (retrofit); (c) restricting power output or percent RDF; (d) modifying the ESP operation (electrical or other characteristics); (e) use of additives or conditioning agents to improve collectability of the particulates (i.e., resistivity); and (f) using fuel of different characteristics (either coal or RDF).

Gaseous stack emissions have also been tested. The only effects noted from the burning of refuse was a moderate increase in Cl⁻.

SO_2 emissions based on gram of SO_2/10⁶ joule heat input exceeded federal regulations for new sources and several individual state regulations for both existing and new sources of the size of the Neramac boiler. The slight reduction in SO_2 stack gas concentration expected when the low sulfur RDF was substituted for the higher sulfur coal were not observed, probably because of data scatter. Burning of RDF should help reduce SO_2 emissions, but such reductions would probably not be sufficient to meet regulations.

A shift to lower sulfur coal or the installation of an SO_2 control system are the viable options for achieving compliance with SO_2 emission regulations.

Few control methods are available for specific, potentially hazardous pollutants that may be emitted from power plants in vapor form. SO_2 scrubbing systems may be effective in controlling some of these pollutants (e.g., Cl), but additional research will be needed to develop appropriate control methods.

The disposal of fly ash resulting from the combined firing of coal and RDF may present problems, especially if a poorly maintained landfill is used as a disposal site. The changes and increases in trace element concentrations in the fly ash that result when RDF is used to supplement coal may increase leaching problems in landfills, and special disposal procedures might be required.

Bottom ash that results from firing coal or coal plus refuse is sluiced from the boiler into an ash pond. In this pond, the bottom ash settles out and the liquid is discharged into a nearby river. Therefore, this operation represents two pollution control problems--bottom ash residue and liquid effluent.

Disposal of bottom ash residue will require more area when burning coal and RDF because of the large increase in the quantity of bottom ash. Increased concentrations of some pollutants that result from combined firing may increase potential leaching problems in landfills.

Tests by the Union Electric Company showed that of many parameters evaluated for the refuse ash pond effluent, only three did not meet guidelines proposed by the State of Missouri. These were BOD, DO, and TSS. Twelve other parameters, for some of which there are no guidelines, are higher in the coal plus RDF ash pond effluent than in the coal ash pond effluent. These include ammonia, boron, calcium, COD, iron, manganese, and total organic solids. Thus it is likely that treatment facilities will be necessary in future plants to control this pollution problem.

Aeration of a coal/RDF ash pond might be needed to improve BOD and dissolved oxygen. Flocculation techniques might also be required to meet regulations on suspended solids and possible future regulations on the content of specific materials in the effluent.

Processing plant.--There are four potential pollution problems at the refuse processing plant:

- Nonferrous materials hauled to landfill
- Water discharge from washdown operations
- Air emission for the air classifier cyclone and hammermill cyclone
- Noise levels

Nonferrous materials (mainly metals) are hauled to landfill, but they represent only about 8% of the raw refuse received. Studies are being considered for evaluating leachability of this stream, but it is not expected that they will present any special problem in this regard, especially not in comparison with landfilling of raw refuse.

Water discharge from washdown operations has been studied, and increases in TSS, BOD, and COD were indicated. However, the quantity of effluent is small (≈ 2,000 gal.) and occurs only one to two times per week, so it is not a significant problem for this size system.

Air emission tests on the hammermill cyclone showed that the particulate emissions are negligible--on the order of 0.00015 to 0.00098 kg/min. However, particulate emissions from the classifier cyclone were significant. These averaged 0.38 kg/min, equivalent to an emission of 0.62 g/kg of raw refuse. A need for controlling or reducing emissions from this source exists.

Noise level measurements were made at several locations around the processing plant, and several of these were above 90 dBA. But these levels did not occur where operators would be subjected to them for periods exceeding those prescribed by Occupational Safety and Health Administration regulations.

NO_x and Oil--

For combined firing of oil and refuse, it is believed that particulate levels will greatly exceed existing standards for fossil-fuel-fired boilers. Experience with the St. Louis/Union Electric combined firing demonstration of coal and refuse indicates that gaseous emissions of CO, CO_2, NO_x, and organics will be relatively unchanged. Although chlorides, mercury vapor, and trace metals will be monitored in demonstration oil-refuse firing studies, particulate control appears to be the most difficult problem. ESP's, cyclones, and scrubbers may be used as controls.

Electrostatic precipitators--The most probable units for oil-refuse combined firing tests are those with ESP control. The efficiency of an ESP for combined firing of oil and refuse is uncertain, however, because of the significantly lower sulfur content of both the oil and the refuse. When oil is fired in the boilers, the efficiency of an ESP designed for 99% efficiency for firing of pulverized coal drops to about 50%, according to tests made by the Consolidated Edison Company, New York. This disparity is believed to be due to the low sulfur content of the fuel oil and the extremely small particle size of the particulates. Other utility companies have also reported ESP efficiencies for oil firing to be around 50% to 60%. However, for combined firing with refuse, the efficiency of an ESP is expected to increase because of the increased particulate loading as well as the increased moisture content of the flue gases. The designers of an ESP for combined oil-refuse

firing in a unit in Stuttgart (West Germany) believe that an ESP designed for 99% efficiency with pulverized coal will result in about 95% collection efficiency for combined firing of oil and refuse.

ESP control modifications may be required for oil-refuse firing. Major requirements for precipitators for stack gases from oil as compared to coal may include reduction in velocity by about 50% or longer gas treatment path, higher operating current, increased rapping intensity, etc.

Cyclone control--Generally speaking, cyclone control is more effective for larger particulate than that encountered in oil firing. However, cyclones are frequently used as precleaning devices for both ESP and high efficiency scrubbers. Tests on No. 6 residual oil-fired boilers (Franklin Station, Rochester, Minnesota) using Zurn TA Mechanical Collectors resulted in 85.7% and 87% collection efficiency with and without fuel additives, respectively. No special operating problems were noted. A large number of cyclone installations are reported in oil-fired utility boilers in Europe. Collection efficiency is between 85% and 92% during sootblowing, and between 70% and 90% during normal operation (finer particulate). Both the European and American test reports are for low excess air operation (< 20% excess air), which yields an increased fraction of coarse particulates.

High efficiency scrubbers--As a result of recent EPA-sponsored tests at Boston Edison's Mystic Station Unit No. 6 and TVA's Shawnee Wet Limestone Scrubbing Test Facility, a fair amount of information is available on performance of high efficiency wet scrubbers in controlling particulate from oil firing. Reported collection efficiencies at Mystic No. 6 are: particulates, 88.5% to 90.6%; SO_2, 97.6% to 99.6%. Pressure drop across the Chemico venturi scrubber is 24.13 cm H_2O at 175 MW load, and 16.51 cm H_2O at a reduced load of 85 MW. Fractional efficiency data obtained in smaller scale tests at the Shawnee Test Facility appear to be reasonably consistent with these test results.

Lack of precise information about the particulate size distribution and other properties from combined oil-refuse firing prevents an estimate of fractional control efficiency for different control devices at this time. There is presently no direct experimental data on control of particulates and other effluents from combined oil and municipal solid waste (MSW) firing.

Recommended Reading

The following articles and reports are suggested for additional information:

1. Funk, H. D., and J. H. Russell, "Operating Experience of the Ames, Iowa, Resource Recovery Plant," paper presented at the 82nd Annual A.I.Ch.E. Meeting, September 1976.

2. Glatz, G. E., V. G. Murphy, W. R. Abraham, J. G. Hill, Energy Recovery from Solid Wastes: Air Pollution, draft report prepared by Ames Laboratory and Iowa State University for U.S. Energy Research and Development Administration, Washington, D.C., February 1977.

3. Gorman, P. G., L. J. Shannon, M. P. Schrag, D. Piscus, "St. Louis Demonstration Project Final Report: Power Plant Equipment Facilities and Environmental Evaluations," Vol. II, prepared under EPA Contract No. 68-02-1871, July 1976.

4. Jackson, J. W., "A Bioenvironmental Study of Emissions from Refuse Derived Fuel," U.S. Air Force Health Lab, Prof. Report No. 76M-2, Project No. AAF-520, January 1976.

THERMOCHEMICAL (PYROLYSIS) PROCESSES

System Description

Pyrolysis can be generally defined as thermal decomposition in an oxygen-starved environment. The process is a complex one of several simultaneously occurring chemical reactions, and it is poorly understood. Products of pyrolysis can be combustible gas, liquid, or solid; therefore, pyrolysis offers an option for various types of fuels in waste-to-energy systems.

Principal characteristics of pyrolysis processes vary and include such factors as bed type, heating method, and pyrolysis temperatures. Bed types that have been commonly used are fixed (shaft), rotary kiln, and fluidized bed; and both direct and indirect methods of supplying heat have been employed. In general, fluidized-bed processes require direct contact with a heating medium, whereas fixed-bed systems can be heated directly or indirectly. The carriers that have been utilized for direct heating are steam, air, recycled gases, sand, and metal balls. Figure 3 presents a general schematic diagram for pyrolysis systems, and Table 6 delineates some of the pyrolysis processes.

Among all the pyrolysis systems shown in Table 6, the Occidental system in San Diego, the Torrax system in New York, the Union Carbide system in West Virginia, and the Landgard system in Baltimore are the best known. Based on recent information,[1] the San Diego Gas and Water and Electric Company has proposed a 21-month test program to assess the impact of combusting pyrolytic oil (from the Occidental flash pyrolysis unit) on SO_2 and NO_x

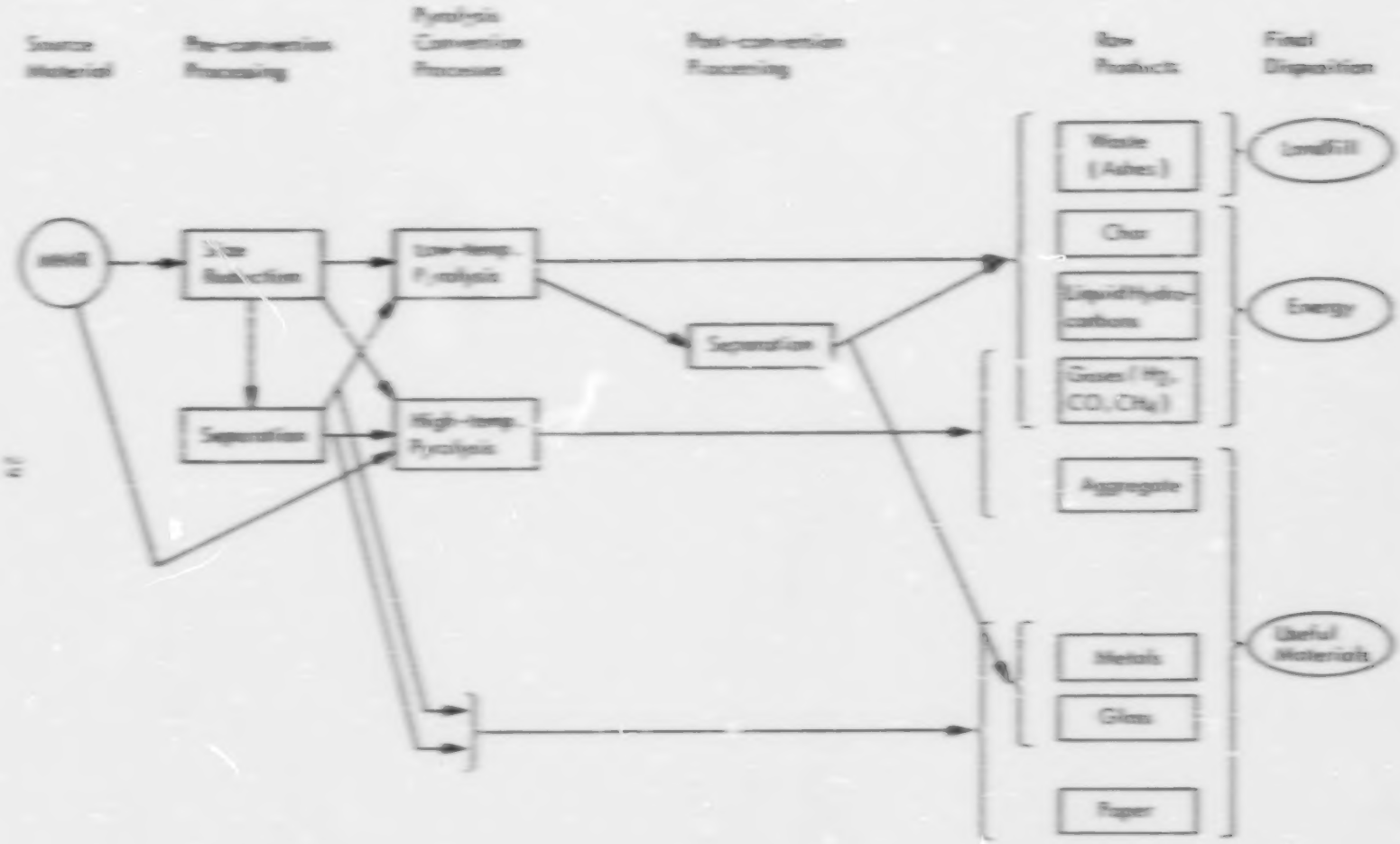

Figure 1. Schematic diagram of pyrolysis of refuse.

TABLE 6. PYROLYSIS PROCESSES

Location	Capacity mt/day	Processing steps[a]	Products
Baltimore, Maryland	907.18	SH, MS	Steam, ferrous, glass, aggregate
San Diego County, California	181.44	SH, AC, MS, OS, FF	Pyrolytic oil, ferrous and non-ferrous, glass
Seattle, Washington	1360.--	SH	Ammonia, ferrous
South Charleston, West Virginia	181.44	SH, MS	Gas, ferrous
Riverside, California	45.36	SH	Gas electricity
Westchester County, New York	2986.51	SH	Gas, steam

a SH, shredding; AC, air classification; MS, magnetic separation; SC, screening; OS, other mechanical separation; FF, fourth fraction; UK, unknown.

emissions. The Georgia Tech. system has had problems operating in the portable mode, but one unit is operating successfully 6 days/week and 24 hr/day in the stationary mode.[22] This unit is fired with wood wastes. Other fuels that have been successfully used in the Georgia Tech. pyrolysis reactor include cotton gin wastes, MSW and tires, MSW and sewage sludge, and MSW and paper mill sludge. The Torrax system has been utilized in Europe on a commercial scale but has not yet reached that level in the United States. The Union Carbide Purox system is close to being commercially utilized, and the process has been successfully demonstrated on a 200 ton/day plant at Charleston, West Virginia.[19] The system can use shredded MSW or shredded MSW and sludge to yield an inert slag and a fuel gas with a heating value of approximately 1.3×10^7 J/m^3. The Monsanto system is the largest of all existing pyrolysis systems (907.18 mg/day), but it is being plagued with severe operational problems.[21]

Pollution Potential

Pollutants from pyrolysis systems are poorly characterized. Depending on the specific process, the major pollutant streams can be air, solid, or liquid. Air emissions can consist of particulates and gases in the form of HCl, H_2S, and NO_x. The solids can contain undesirable leachates, and wastewater from pyrolysis systems can be high in BOD, COD, alcohols, phenols, and other organic compounds. Gas cleaning systems commonly used in pyrolysis processes include wet scrubbers and ESP's, and wastewater treatment systems are usually site specific.

Pyrolysis systems that requires processing of waste (e.g., Purox, Occidental) generate pollutants during the processing steps. These pollutants will be characteristic of those generated in MSW processing to obtain RDF.

Pollutants generated in the pyrolysis reactor and in subsequent operations of the process include solids in the form of slag, particulate and gaseous pollutants in the gas stream, and water effluents.

In the Purox System, solids generated are slag from the reactor and sludge from wastewater treatment. The amount of slag produced is reported to be 440 lb/ton refuse.[19] An average slag analysis is as follows:[19]

Item	A
MnO	0.1
SiO_2	59.7
CaO	10.1
Al_2O_3	10.5
TiO_2	0.6
BaO	0.2
P_2O_5	0.1
FeO	6.2
MgO	2.2
Na_2O	8.0
K_2O	1.0
CuO	0.2
Miscellaneous	0.7
Total	100.0

The slag is reported to be inert and nonleaching. The gas cleaning train consists of a scrubber and an electrostatic precipitator. Oil from the electrostatic precipitator is recycled to the pyrolysis reactor, and scrubber water goes to a decant tank before being recycled. The wastewater from the decant tank goes to a sewer.

Data on the wastewater pollutant concentrations are apparently not available. Union Carbide claims that their "commercial" Purox module will have the UNOX water treatment unit available and that the pollutant potential of the treated wastewater is inconsequential.[20] However, water effluents from waste pyrolysis processes, if untreated, can pose a significant pollution problem because of the high amount of soluble organic and inorganic compounds. The water effluent from the gas scrubbing system is expected to be high in COD and BOD and is expected to contain alcohols, phenols, aldehydes, and other organic compounds. Potentially hazardous trace elements could also be present, since they are contained in RDF and sewage sludge, both of which can be used as feed materials.

The gas stream might contain particulates even after going through an electrostatic precipitator, but the particulate loading is not expected to be high. The nature of the particulate pollutants in the fuel gas is presently not documented. Analysis of typical Purox fuel gas itself is shown as follows:[19]

Gas	Volume %
H_2	20
CO	40
CO_2	23
CH_4	5
C_2H	5
N_2 and A	1

Gas--higher heating value 1.38×10^7 J/mm^3

The gas has been analyzed for some pollutants, which are identified below:[23]

NO_x < µl/liter

HCl < 1 µl/liter

H_2S = 300 to 600 µl/liter

COS < 1 µl/liter

No major tests have been conducted on the Occidental pyrolysis system to establish its pollution potential. As with the Purox system, the liquid effluent and gas streams are probably the important ones to be tested from a pollution standpoint. Preliminary estimates indicate that SO_2 emissions are about 700 µl/liter; NO_x, about 8 to 1,000 µl/liter; HCl, 100 µl/liter; and particulates, 114.42 mg/mm^3.[23]

The Monsanto Landgard System is also poorly characterized for its pollution potential. The off gases from the pyrolysis kiln go to an afterburner, and the heat released is directed to two waste heat boilers. Waste gases from the boilers go to a wet scrubber. The scrubber has not performed satisfactorily. In addition, there have been problems involving metallic residues in the pyrolysis gas stream and excessive slagging of inerts in the solids discharge system.

The Torrax Pyrolysis System and the Georgia Tech. Pyrolysis System have not been tested for environmental pollution either. The Torrax system is similar to the Purox system, except that air rather than oxygen is used for oxidizing the char in the bottom of the vertical reactor. A 68 Mg/day Torrax demonstration system has been tested at Orchard Park, New York, and a 181.4 Mg/day facility is in Luxembourg; but no emission test data are reported.

The Georgia Tech. system now uses wood waste (sawdust and bark) as fuel and operates three shifts/day, 7 days/week. The system is a 45.35 Mg/day demonstration plant at Cordele, Georgia, and it is owned and operated by the Tech. Air Corporation. The char and pyrolytic oil produced are sold. A portion of the gas produced is used for drying the feed, and the rest is flared. Knight et al.[74] report that an analysis of the combustion stack gases was made and that it meets all the Federal standards. However, no details are provided on gas composition or the results of the analysis.

From the above discussion, it is clear that adequate measured data are not available to make an assessment of the environmental impact of pyrolysis systems. An engineering analysis using the source severity concept outlined in Appendix A can be used to obtain an insight to the potential impacts of the pyrolysis systems. The same approach can be used for any waste-as[illegible] system. An example of the procedure is presented in Appendix B.

Pollution Control Technology

Control technology information on pyrolysis systems is minimal. A discussion of the Purox system follows to demonstrate what is available.

Pollutants requiring control from the Purox system are liquid effluents, air emissions, and solids in the form of slag. In addition, there will be emissions from preprocessing of MSW, which can be controlled by using techniques similar to those discussed earlier under MSW and coal for preprocessing MSW.

Liquid effluents from the Purox system are made up of scrubber water and the condensate water, both of which go to a quench tank for recycling and disposal. This wastewater stream is expected to have high concentrations of BOD, COD, phenols, and other organics, and it will require treatment before disposal. Union Carbide claims that their commercial Purox units will have the UNOX wastewater treatment facility available and that, therefore, this should not cause any environmental concerns.[20]

Control of air emissions from the Purox system should not pose any major difficulty, since the air stream is the product gas stream. Some trace elements may be present in the particulates, even after passing through the wet scrubber and ESP, but no data are as yet available.

The slag from the Purox system is claimed to be free of leachates and could be disposed of in landfills or as a construction material.

Recommended Reading

The following major articles and reports are suggested as sources for additional information:

1. Alpert, S. B., "Pyrolysis of Solid Waste: A Technical and Economic Assessment," Stanford Research Institute, West Virginia University Report No. WVU-ENG-CHE-73-01, September 1972.

2. Anderson, J. E., "The Oxygen Refuse Converter--A System for Producing Fuel Gas Oil, Molten Metal, and Slag from Refuse," 1975 National Incinerator Conference, ASME Incinerator Division, Miami, Florida, May 1975.

3. Hammond, V. L., "Pyrolysis--Incineration Process for Solid Waste Disposal," Battelle Pacific Northwest Laboratories, Richland, Washington, December 1972.

4. Hammond, V. L., and L. E. Nudge, "Feasibility Study of Use of Molten Salt Technology for Pyrolysis of Solid Waste," EPA Contract No. 68-03-0145, Battelle Pacific Northwest Laboratories, Richland, Washington, April 1975.

5. Knight, J. A., M. D. Bowen, and E. E. Purdy, "Pyrolysis--A Method for Conversion of Forestry Wastes to Useful Fuels," presented at the Conference on Energy and Wood Products Industry, Forest Products Research Society, Atlanta, Georgia, November 1976.

6. Levy, S. J., "Pyrolysis of Municipal Solid Waste," Waste Age, October 1975, pp. 14-20.

7. Preston, G. T., "Resource Recovery and Flash Pyrolysis of Municipal Refuse," Waste Age, May 1976, pp. 83-98.

WOOD FUEL BOILERS

System Description

In the manufacture of lumber, about 50% of the material from the log is removed to produce sound lumber.[25] Though the total waste usually averages approximately 50%, distribution of the different types of waste such as slabs, edging, trimming, bark, sawdust, and shavings, may vary depending on mill conditions and product desired. The mills frequently use sawdust or sawdust and shaving mixtures for steam production because they can be burned without further processing. The remainder of the waste products requires further size reduction in a "hog" to facilitate storage, feeding, combustion, etc. These newly sized products together with varying percentages of sawdust and shavings present constitute "hog fuel."[25] Table 7 analyses hogged fuels, including moisture content, on an "as-received" as well as "air-dried" basis. The heating value is also shown.

TABLE 7: ANALYSES OF HEDGED FUELS[29]
(%, except as noted)

Item	Type of fuel: Western hemlock	Douglas Fir	Pine sawdust
Moisture, as received	57.9	35.9	---
Moisture, air-dried	7.7	6.5	6.3
Proximate analysis, dry:			
Fuel			
Volatile matter	71.2	82.0	79.4
Fixed carbon	23.6	17.2	20.1
Ash	2.2	0.8	0.5
Ultimate analysis, dry:			
Fuel			
Hydrogen	5.8	6.3	6.3
Carbon	50.4	52.3	51.8
Nitrogen	0.1	0.1	0.1
Oxygen	41.4	40.5	41.3
Sulfur	0.1	0	0
Ash	2.2	0.8	0.5
Heating value, dry: (joule/kg)	20.05×10^6	21.05×10^6	21.24×10^6

Reports indicate that, based on sales of wood-burning and other types of boilers, wood is the most significant fuel other than coal, oil, or natural gas. The most prevalent size for wood-fired boilers is reported to be in the range of 113.37 to 1133.7 kg steam/min.[1] The most common firing method for wood-fired boilers in all size ranges is the spreader stoker, with overfeed stokers also being common in sizes less than 1889.5 kg steam/min.[1]

There are several important considerations in burning wood. These relate to the fouling potential of wood as a result of its ash composition. Wood ash is high in CaO (50% to 60%), and high in Na_2O and K_2O (4% to 7%).[1] Generally speaking, substituting wood for residual fuel oil will increase problems with fouled heat-receiving surfaces. Burning wood in boiler furnaces designed for pulverized coal will not be likely to pose fouling problems worse than with coal alone, except that alkalies may tend to accumulate more rapidly in the cooler parts of the boiler, such as the superheater.[1]

The substitution of wood firing in existing coal-fired stoker boilers presents the fewest problems. In most cases, only minor modifications to the boiler are necessary, such as addition of a wood-feeding system or firing ports. Hogged fuel of less than about 5.08 cm in size, with a minimum of slack (less than 0.635 cm) should be acceptable to most spreader and overfeed-type stokers.[1]

Wood can also be fired in suspension in boilers designed for pulverized coal or heavy oil. The wood should be reduced in size to less than 0.635 cm and dried as much as possible to insure rapid combustion. Most suspension wood-fired boilers have a small grate at the base of the unit to insure complete burnout of any wood chips that do not burn in suspension. Firing wood in boilers designed for natural gas or light fuel oil would represent a difficult problem since extensive boiler modifications will have to be undertaken to provide ash handling capabilities.

Pollution Potential

The combustion of wood will result in particulate pollutant emissions and ash in the form of captured fly ash and bottom ash. Wood, unlike coal or oil, has a negligible sulfur content and should therefore create no SO_2 problems. Nitrogen oxide emissions should also be lower than that observed during coal combustion because of the low nitrogen content of wood (see Table 8).

Typical emission factors for wood and bark combustion, as reported in the literature, are presented in Table 9.[1] Values presented in Table 9 are uncontrolled emissions. Based on these values, it appears that control of criteria pollutants from wood or bark combustion should pose no serious problems.

| | | |

TABLE 9. EMISSION FACTORS FOR WOOD AND BARK[a] COMBUSTION IN BOILERS WITH NO REINJECTION[1]

Pollutant	Emission (g/kg)
Particulate[b]	12.5-15
Sulfur oxides (SO_2)[c]	0-1.5
Carbon monoxide	1.0
Hydrocarbons[d]	1.0
Nitrogen oxides (NO_2)	5

a Moisture content assumed to be 50% in wood and bark.
b This number is the atmospheric emission factor without fly ash reinjection. For boilers with reinjection, the particulate loadings reaching the control equipment are 15 to 17.5 g/kg fuel with 100% reinjection.
c Use 0 for most wood, and higher values for bark.
d Expressed as methane.

Particulate emissions from wood-fired boilers can vary, depending on the extent of char reinjection, boiler type, excess air used, wood waste type (e.g., logs, sawdust, chips) and wood moisture content. Hall et al.[1] report that the single most significant factor is probably the extent of char reinjection utilized.

Char reinjection systems, which return collected particles to the combustion zone to achieve more complete combustion of the carbon, represent a compromise between two conflicting objectives. While reinjection increases boiler efficiency and minimizes the emission of uncombusted carbon, it also increases boiler maintenance requirements, decreases the average fly-ash particle size, increases the dust load to the collector, and makes collection more difficult.[1] Properly designed reinjection systems should separate the sand and the char from the exhaust gases, reinject the larger carbon fraction to the boiler, and reinject the fine sand particles to the ash disposal system.

Pollution Control Technology

Emissions from hog-fuel boilers primarily consist of particulates. The other environmental aspect is the generation of captured fly ash and bottom ash, which can be disposed of in landfills.

Fly ash particulates from hog-fuel boilers are light in density and larger in size than fly ash from coal-fired boilers.[1] Also, particulate emissions from wood-fired systems can vary depending on the extent of char reinjection, boiler type, excess air, wood waste type, moisture content, etc. Because of these variations, a specific dust loading cannot be established. It is reported that dust loadings range from 1146.17 to 11,441.7 mg/m^3 and that multicyclones are the sole source of particulate removal for most hogged fuel boilers.[1] Wet scrubbers with moderate pressure drops can also be used effectively on this source, since particle size is considered to be large. However, this may result in secondary wastewater pollution. High temperature fabric filtration systems may also be another alternative control system. The use of ESP's, however, will depend on particle resistivity, which for this source might be in the lower range.

Recommended Reading

The following references are suggested for more information on wood-fired boilers:

1. Hall, E. H., et al., "Comparison of Fossil and Wood Fuels," EPA Report No. EPA-600/2-76-056, March 1976.

7. U.S. Department of Agriculture, Forestry Service, "Final Report on the Feasibility of Utilizing Forest Residues for Energy and Chemicals," by Forest Service, USDA, National Science Foundation Report No. NSF-RA-760013, March 1976.

BIOCHEMICAL SYSTEMS

System Description

Controlled anaerobic digestion is a biological process whereby organic matter decomposes in a regulated oxygen-deficient environment. Since the organic matter in municipal solid waste is predominantly cellulose, conversion of solid waste to methane by anaerobic digestion may be chemically represented as:

$$C_6H_{10}O_5 + H_2O \longrightarrow 3\ CO_2 + 3\ CH_4$$

The system for converting solid waste to methane essentially consists of feed preparation, digestion, gas treatment, and effluent disposal. Figure 4 is a conceptual flow sheet of the process.[36]

On a commercial scale, this anaerobic digestion process is being designed and developed by Waste Management, Inc., of Oak Brook, Illinois, for ERDA. The facility is located in Pompano Beach, Florida. About 80% of the design has been completed, and equipment procurement is 50% complete; construction has also begun.[37] The shredding system now operates at 272.10 Mg/day but will be expanded to handle 544.2 to 725.6 Mg/day.[37] The system will use mechanical mixing in the digester rather than a gas mixer, as originally proposed.

Pollution Potential

Pollutants from the anaerobic digestion process include those that result from preprocessing of solid waste, wastewater, and cake from the slurry dewatering system.

Slurry dewatering can be accomplished either by vacuum filtration or centrifugation.[38] Both processes result in filter cake solids and wastewater for disposal. Filter cake solids can be used for landfills or, preferably, they can be incinerated to generate steam. Incineration, in turn, will result in particulate pollutants and ash disposal, but techniques for particulate pollutant control from incinerators are well established and therefore should eliminate any environmental concerns. Wastewater from the slurry could be high in pollutants, and no data are presently available to characterize pollutants in this effluent stream.

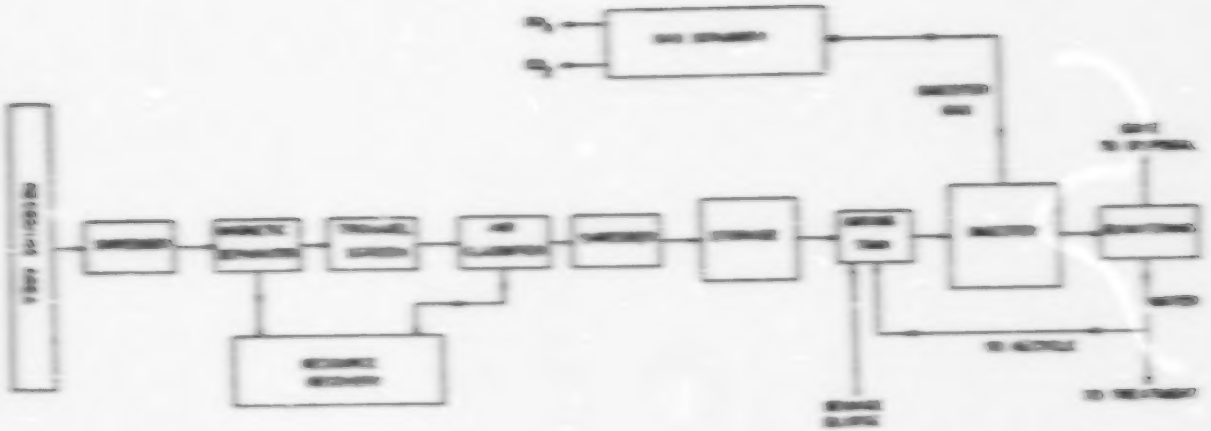

Figure 4. Block diagram of the anaerobic digestion system.[5]

The product gas from the digester (i.e., CH_4) contains CO_2 and trace quantities of H_2S. These two acid gases must be removed to upgrade the product gas to pipeline quality. Depending on the technique employed for acid gas removal, pollutants are likely to be encountered, and adequate provision should be made for their removal and/or ultimate disposal in an environmentally acceptable manner.

Pollution Control Technology

Controls are required to treat wastewater from dewatering sludge. The liquid effluent can be partially recycled, and the remainder can go to a waste treatment plant for clarification and purification. If not treated, the wastewater can cause severe environmental problems.

The filter cake from the dewatering operation can either be incinerated or sent to a landfill. The latter disposal technique should be investigated further to determine if potentially hazardous bacteria or leachates are present.

Air emissions can result from upgrading of digester gas to pipeline quality methane, but no information is available on these control technology aspects.

Recommended Reading

The following references are suggested for information on biochemical waste utilization systems:

1. Bissette, G., Urban Trash Methanation Background for a Proof-of-Concept Experiment, Mitre Corporation, NSF/RANN Contract No. NSF-C938, February 1975.

2. Hecht, N. L., and D. S. Duvall, Characterization and Utilization of Municipal and Utility Sludges and Ashes, Vol. I, II, and III, U.S. Environmental Protection Agency Report No. EPA-670/2-75-033a, b, and c, Cincinnati, Ohio, May 1975.

3. Pfeffer, J. T., and J. C. Liebman, "Energy from Refuse by Bioconversion, Fermentation and Residue Disposal Processes," Resource Recovery and Conservation, 1:295-313, 1976.

ADVANCED COMBUSTION SYSTEMS (CPU-400)

System Description

Since 1967, the Combustion Power Company (Menlo Park, California) has been involved in developing an advanced combustion system to convert the energy in refuse to electrical power. The system uses a fluidized bed incinerator as the combustor and a gas turbine-generator to produce electrical power. At commercial scales, the system is to be capable of converting the heating value of 544.3 Mg/day of solid waste into 9 to 12 MW of useful electrical power while also recovering secondary materials from the waste stream. Development has progressed to a pilot-scale facility capable of converting 90.7 Mg/day of solid waste into energy.[21]

The pilot system has two modules, one for solid waste processing and the other a power module. The waste processing module has two shredders (745.7×10^3 w and 559.3×10^3 w), an air classifier, and a materials recovery system. After wastes are shredded and air-classified, the light fraction is pneumatically transported to the shredded waste storage vessel. A material recovery system is used to recover steel and aluminum. A glass-rich fraction and a nonferrous-rich fraction are also separated and are available for further recovery operations.[21]

The power module consists of a vertical, cylindrical, fluidized bed combustor and its feed system, a three-stage gas cleaning system, a turbogenerator, and an automatic control system. The gas cleaning system is made up of two parallel 0.91 m cyclones, two parallel 0.76 m cyclones, and a granular filter. A four-stage, axial-flow, gas turbine is used for extracting energy from the hot gas stream to drive an air compressor and to run a 1,000-kw electrical generator.[21]

Pollution Potential

Processing of waste that is required to generate refuse feed to the fluidized bed combustor will result in pollutants that have been identified in an earlier section.

A high degree of particulate removal from the combustor exhaust gases is required before use in the turbine generator set. Therefore, fly ash collected upstream of the turbine can create a solid waste disposal problem if it cannot be disposed of properly. Particulate emissions from the turbine exhaust should be of minimum concern.

The only other potential pollution problem could result from gases from the turbine exhaust. A summary of some gaseous components in the turbine exhaust is given as follows:[23]

Gas constituent	Low-pressure test	High-pressure test
O_2	13.6%	16.1%
CO_2	5.8%	5.2%
CH_4	< 30 µl/liter	< 30 µl/liter
SO_2	0 µl/liter	2 µl/liter
HCl	161 µl/liter	63 µl/liter

Pollution Control Technology

Hot combustion gases pass through a three-stage cleanup before entering the gas turbine:

First stage--two parallel, 0.91 m diameter cyclones,

Second stage--two parallel, 0.76 m diameter cyclones, and

Third stage--granular filter (aluminum oxide).

The granular filter bed is continuously regenerated by slowly moving downward through a screen. It is subjected to a cleanup process and then reenters at the top of the bed. Recent information indicates that this system is currently not operating because of structural problems.[29]

Particulate (including sand from the combustion bed) collected by the three-stage separators is pneumatically conveyed to a sand bin (cyclone), which exhausts to a baghouse filter. These control options appear viable and should cause no environmental insults. Dust from the shredded waste storage bin is controlled by two small cyclones.

No water effluents are generated in the CPU-400 process except for cooling bearings.

Solids for disposal from the CPU-400 system are residue from waste shredding and subsequent recovery operations. Magnetic materials, aluminum, and glass are recovered. The residue goes to a landfill.

Recommended Reading

1. Trethaway, W., "Energy Recovery and Thermal Disposal of Wastes Utilizing Fluidized Bed Reactor Systems," in Proceedings of the 1976 National Waste Processing Conference, Boston, Massachusetts, May 23-26, 1976.

SECTION 5

STATUS OF WASTE-TO-ENERGY CONVERSION SYSTEMS

Table 10 lists the different waste conversion systems, their locations, plant capacities, processing operations, and products. The table also includes the capital cost of each system and its developmental status. For most systems, no emission data are available.

The systems presented in Table 10 include those that are operational as well as those that are in an advanced planning state. Some proposed systems may not be included since the listing here is not intended to be a comprehensive presentation of systems.

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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3. Environmental Assessment of Waste-to-Energy Processes, Monthly Report No. 6, Prepared by Midwest Research Institute, EPA Contract No. 68-02-2166, April 1977.

4. Nashville Thermal Transfer Corporation Compliance Test Report, Unit No. 3 - Incinerator, prepared by Particle Data Laboratories (PDL), Ltd., Elmhurst, Illinois, under PDL Project No. 15408, September 1976.

5. Bradway, R. M., and R. W. Coss, Fractional Efficiency of a Utility Boiler Equipped, Whole Generating Plant, NTIS Document No. PB 246641, August 1975.

6. Gordon, G. E., W. H. Zoller, and E. S. Gladney, "Abnormally Enriched Trace Elements in the Atmosphere," presented at the 7th Annual Conference on Trace Substances in Environmental Health, University of Missouri, Columbia, Missouri, June 1973.

7. Roseke, G. G., "Nashville Incinerator Performance Tests," in Proceedings of the National Waste Processing Conference, Boston, Massachusetts, May 1976.

8. Kaplan, L., and F. Francoeur, "Determination and Evaluation of Stack Emissions from Municipal Incinerators," presented at the 68th Annual APCA Meeting, Boston, June 1975.

9. Jackson, J. W., A Bioenvironmental Study of Emissions from Refuse Derived Fuel, Prof. Report No. 76M-2, Project No. AAF-520, USAF Environmental Health Laboratory, January 1976.

10. Gaieski, J. B., and M. P. Schrag, Performance of Emission Control Devices on Boilers Firing Municipal Solid Waste and Oil, EPA Report No. EPA-600/2-76-209, July 1976.

11. Hall, E. H., G. M. Allen, D. A. Ball, J. E. Burch, H. M. Conkle, W. T. Lawhon, T. J. Thomas, and G. R. Smithson, Jr., Comparison of Fossil and Wood Fuels, EPA Report No. EPA-600/2-76-036, March 1976.

12. Garutti, A. A., and E. R. Kaiser, "Concentration of 30 Gaseous Chemical Species in the Flue Gas of a Municipal Incinerator," J. APCA, 22(6), April 1972.

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14. Kinsley, E. G., Source Assessment: Prioritization of Stationary Air Pollution Sources--Model Description, EPA Report No. EPA-600/2-76-032a, February 1976.

15. Kinsley, E. G., G. M. Moscowitz, J. L. Delaney, R. F. Quill, and R. L. Sanders, Air, Water, and Solid Residue Prioritization Models for Conventional Combustion Sources, NTIS No. PB-257103, July 1976.

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17. MacAdam, W. K., and S. E. Stanbrod, Jr., "Design and Operational Considerations of a Plant Extracting Energy from Solid Waste for Industrial Uses," presented at ASME Industrial Power Conference, May 1975.

18. Chambliss, G., "Paper on Nashville Testing Experience," presented at the Engineering Foundation Conference on Present Status and Research Needs in Energy Recovery from Wastes, Oxford, Ohio, September 1976.

19. Fisher, T. F., M. L. Kasbohm, and J. R. Rivero, "The Purox System" presented at the National Waste Processing Conference, Boston, May 23-26, 1976.

20. Private communication with Dr. Charles Moses of Union Carbide at a project meeting on the subject program at San Francisco, December 3, 1976.

21. Wilson, E. H., and H. H. Freeman, "Processing Energy from Wastes," Environ. Science and Tech., 10(5):430, May 1976.

22. Private communication with D. J. Lohuis, President, Tech. Air, Chamblee, Georgia, January 6, 1977.

23. Wilson, E. H., J. H. Leavens, H. W. Snyder, J. J. Breheny, and E. F. Whitman, Utilization of Wastes as Fossil Fuel Energy Substitutes, EPA Contract No. 68-02-2101 to Ralph H. Parsons Company, draft final report.

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APPENDICES

APPENDIX A. SUMMARY OF SOURCE SEVERITY CONCEPT FOR ENVIRONMENTAL IMPACT ANALYSIS.

Analysis of the environmental impact of pollutants is hindered by the lack of well-defined allowable ambient concentrations or population exposure limits. There are several recent reports in the literature that discuss methods to estimate the impact of pollutants based on some type of prioritization procedure.[14-16]

The impact factor developed by Rimstus[14] is defined as the sum of the lengths of the individual severity factors associated with the point sources within the source type. Thus:

$$I_s = \sum_{j=1}^{K_s} F_j \left[\sum_{i=1}^{N} \left(\frac{\bar{x}_{ij}}{P_i} \right)^2 \frac{x'_{ij}}{P_i} \right]^{1/2} \qquad (1)$$

where I_s = impact factor, persons/km^2

K_s = number of sources emitting materials associated with source type s

N = number of materials emitted by each source

F_j = population density in the region associated with jth source, persons/km^2

$\bar{x}_{ij}$ = calculated maximum ground level concentration of the ith material emitted by the jth source, g/m^3

P_i = environmental hazard potential factor of the ith material, g/m^3

x'_{ij} = ambient concentration of the ith material in the region associated with the jth source

S_i = corresponding standard for the ith material (used only for criteria emissions, otherwise set equal to one)

As shown in Eq. (1) the impact factor takes into account various criteria such as number of sources emitting a pollutant, population density, hazard potential, ground level and ambient concentrations, etc. The assumptions and limitations of the model are detailed by Elmutus.[14]

A simpler method is identified by Elmutus et al.,[16] for determining the severity of pollutants. For example, the maximum ground level concentration, χ_{max}, for elevated point sources is given by:

$$\chi_{max} = \frac{2Qe}{\pi e u h^2 \sigma_y} \qquad (2)$$

where χ_{max} = maximum ground level concentration, g/m^3

π = 3.1416

e = 2.72

u = wind speed (m/sec) = assumed to be 4.5 m/sec

h = emission height (m)

σ_z = vertical dispersion coefficient, m

σ_y = horizontal dispersion coefficient,

Q = emission rate (g/sec)

The average concentration, $\bar{\chi}$, is a function of sampling time, t_1, and it can be related to the maximum concentration, χ_{max}, as follows:[17]

$$\bar{\chi} = \chi_{max}\left(\frac{t_1}{t_2}\right)^p \qquad (3)$$

where t_1 = 3 min

t_2 = reference time period

p = 0.17

the source severity(s) is defined as[16]

$$S = \frac{\bar{\chi}}{\rho} \tag{4}$$

where $\bar{\chi}$ = average concentration as defined above

ρ = hazard potential factor

Using Eqs. (2), (3), and (4) the severity equations for criteria pollutants can easily be developed. Let us take CO as an example.

Since the primary standard for CO is for a 1-hr averaging time, t_2 = 60 min in Eq. (3). This results in:

$$\bar{\chi} = \chi_{max}\left(\frac{1}{60}\right)^{0.17} \tag{5}$$

Substituting Eq. (2) in Eq. (5)

$$\bar{\chi} = \frac{2Q\pi_0}{\pi e u h^2 \sigma_y}\left(\frac{1}{60}\right)^{0.17} \tag{6}$$

In Eq. (6), $\sigma_z = \sigma_y$ because the national atmospheric stability is approximately neutral. This reduces Eq. (6) to

$$\bar{\chi} = \frac{2Q}{\pi e u h^2}\left(\frac{1}{60}\right)^{0.17} \tag{7}$$

Substituting for π, e, and u in Eq. (7),

$$\bar{\chi} = \frac{(3.12 \times 10^{-2})Q}{h^2} \tag{8}$$

Combining Eqs. (8) and (4),

$$S = \frac{(3.12 \times 10^{-2})\ Q}{\rho h^2} \tag{9}$$

For the criteria pollutants, P is not equal to the primary standard, which is 0.04 g/m^3 for CO.

$$\text{then,} \qquad S = \frac{(3.12 \times 10^{-2})\,Q h^{-2}}{0.04} \tag{10}$$

Further simplification results in

$$S_{CO} = 0.78\,Q h^{-2} \tag{11}$$

Eq. (11) is the severity equation for CO. Similarly, for other criteria pollutants, the severity equations are as follows:[16]

Particulate, $S = 70\,Q h^{-2}$

SO_x, $S = 30\,Q h^{-2}$

NO_x, $S = 315\,Q h^{-2.1}$

Hydrocarbons, $S = 162.5\,Q h^{-2}$

To use these equations, only emission rate (g/sec) and emission height (m) are required.

The severity can also be related to the threshold limit value (TLV). This relationship is shown below,[16]

$$S = \frac{\chi}{P} = \frac{\chi_{max}\left(\frac{t_1}{t_2}\right)^p}{TLV\left(\frac{8}{24}\right)\left(\frac{1}{100}\right)} \tag{12}$$

Further simplification of Eq. (12) results in:

$$S = \frac{3.5\,Q}{(TLV)h^2} \tag{13}$$

Eq. (13) requires knowledge of TLV in addition to emission rate and emission height. For criteria pollutants, ambient air standards have been established. Therefore, TLV was not needed. If the emission height is assumed constant for pollutants from the same source, which is logical, then Eq. (13) reduces to:

$$S = \frac{KQ}{TLV} \qquad (14)$$

where K is a constant. In effect, Eq. (14) is the same as comparing emission rate with TLV.

For water effluents, the severity criterion could probably be represented as:

$$S_W = \frac{Q}{L_{50}} \qquad (15)$$

For solids discharge, the severity equation should probably include a "leachability" factor. Information is limited at the present time to develop and test a hypothetical severity equation for solids based on leachability.

APPENDIX B

ILLUSTRATION OF ENVIRONMENTAL IMPACT ANALYSIS

The Purox system was arbitrarily chosen for this illustration, but the same approach can be used for other waste conversion systems. Pollutant concentrations from Purox effluent streams were estimated based on available data and engineering analysis. The resulting values were then compared with the TLV's to determine which of the pollutants have the most impact. The methodology used in this approach is detailed below.

To estimate the concentration of pollutants from the Purox process, we first had to identify pollutants from such systems. The following list of pollutants are documented in the literature as being present in refuse or are suspected to be in refuse because of their production and consumption patterns. This list is by no means final and is merely intended to illustrate the estimation procedure used in this analysis.

Acrylonitrile
Aldrin/dieldrin
Aluminum
Antimony
Arsenic
Asbestos
Barium
Beryllium
Bismuth
Boron
Bromides
Cadmium
Calcium
Carbon
Cerium
Cesium
Chlorides
Chromium and compounds
Cobalt
Copper and compounds
Cyanides
DDT and metabolites
Dichlorobenzene
Dysprosium
Erbium
Europium
Fluorides
Gallium
Gadolinium
Germanium
Gold
Hafnium
Indium
Iodides
Iridium
Iron
Lanthanum
Lead
Lithium
Lutetium
Magnesium
Manganese
Mercury
Molybdenum
Neodymium
Nickel
Nitrates
Nitrogen oxides
Osmium
Oxygen
Palladium
Phosphorus
Phthalate esters
Platinum
Polychlorinated biphenyls
Praseodymium
Rhenium
Rhodium
Rubidium
Ruthenium
Samarium
Scandium
Selenium and compounds
Silicon
Silver
Sodium

Strontium	Tin	Vanadium
Sulfur	Titanium	Vinyl chloride
Tantalum	Thorium	Ytterbium
Tellurium	Toluene	Yttrium
Terbium	Tungsten	Zinc
Thallium	Uranium	Zirconium

Based on analysis of refuse performed in the St. Louis, study,[2] we were able to identify concentrations for some of the pollutants listed. We assessed these values to be representative for MDF in general and computed the hourly rates of these pollutants entering the Purox process at a refuse feed rate of 9.07 Mg/hr, as shown in Table B-1.

The major assumption made in the analysis is that all of the pollutants are contained in the gas stream. This assumption may not be very realistic; nonetheless, it provides a worst case for consideration and is the most conservative. The next step is to compute, from the hourly rate of incoming pollutant, the pollutant concentration in the flue gas stream leaving the combustor that burns the fuel gas from the Purox system.

To do this, an estimate of the dry flue gas per kilogram of fuel is required. Figure B-1 is a schematic showing the fuel gas produced per Megagram of refuse and the approximate composition of the fuel gas. Based on this composition, the molecular weight of the fuel gas and the resulting gas volume per Megagram of fuel gas combusted, at 30% excess air, were computed. These computations are shown in Tables B-2 through B-5. The main item from [illegible] required for the analysis is the volume of dry flue gas generated per Megagram of fuel gas combusted. This value is found to be 13,618 m^3 for 0.3 Mg of fuel gas for 9.07 Mg of refuse). Using this relationship and the incoming pollutant rates from Table B-1, the pollutant concentrations in the flue gas (in $\mu g/m^3$) were calculated. These data are shown in Table B-6. A dilution factor of 1,000 was further assumed, and the resulting concentrations were compared to the TLV for the various pollutants. Table B-6 also shows 1/10 and 1/100 of the TLV values to be more conservative.

A comparison of the pollutant concentration in flue gas at a dilution of 1,000 with 1/10 and 1/100 of the TLV for the specific pollutant shows that several pollutants may be of little concern. (A dilution factor of 1/1,000 was used to compute the maximum ground level concentration. Dilutions of 1/10 and 1/100 of the TLV were estimated to account for a 40-hr work week and to render the comparison more conservative.) The pollutants whose concentrations are higher than 1/10 and 1/100 TLV and which may be of greater concern are shown separately in Table B-6.

TABLE B-1. CONCENTRATION OF POLLUTANTS IN REFUSE

Element/compound	Amount contained in refuse[1] (µg/g) (except as otherwise noted)	Mg/hr in feed (at 9.07 Mg/hr feed rate)
Acrylonitrile	-	-
Aldrin/dieldrin	-	-
Aluminum	> 1%	-
Antimony	86	0.78
Arsenic	22	0.198
Asbestos	-	-
Barium	1,967	17.703
Beryllium	0.26	0.002
Bismuth	9.3	0.084
Boron	2.77	0.025
Bromine	58	0.522
Cadmium	28	0.252
Calcium	> 1%	-
Cerium	67	0.603
Cesium	2.6	0.023
Chlorine	2,233	20.097
Chromium and compounds	1,993	17.937
Cobalt	330	2.97
Copper and compounds	2,867	25.803
Cyanides	-	-
DDT and metabolites	-	-
Dichlorobenzene	-	-
Dysprosium	4.9	0.044
Erbium	0.67	0.006
Europium	1.10	0.0099
Fluorides (Ft)	667	6.003
Gallium	12	0.108
Gadolinium	0.62	0.0056
Germanium	3.30	0.0297
Gold	-	-
Hafnium	5.1	0.0459
Indium	-	-
Iodides (Iodine)	0.53	0.0048
Iridium	-	-
Iron	> 1%	-
Lanthanum	36	0.324
Lead	2,167	19.503
Lithium	106	0.954

TABLE B-1. (Continued)

Element/compound	Amount contained in refuse[3] (ug/g) (except as otherwise noted)	Kg/hr in feed (at 9.07 Mg/hr feed rate)
Lutetium	1.0	0.009
Magnesium	> 0.83%	-
Manganese	773	6.957
Mercury	-	-
Molybdenum	44	0.396
Neodymium	15	0.135
Nickel	827	7.443
Niobium	15	0.135
Nitrogen oxides	-	-
Osmium	-	-
Palladium	-	-
Phosphorus	> 0.5%	-
Phthalate esters	-	-
Platinum	-	-
PCB	-	-
Praseodymium	5.7	0.051
Rhenium	-	-
Rhodium	-	-
Rubidium	78	0.702
Ruthenium	-	-
Samarium	2.7	0.024
Scandium	1.5	0.0135
Selenium and compounds	3.8	0.0342
Silicon	> 1%	-
Silver	7.1	0.0639
Sodium	> 1%	-
Strontium	587	5.283
Sulfur	> 1%	-
Tantalum	0.63	0.0057
Tellurium	-	-
Terbium	0.73	0.0066
Thallium	0.16	0.0014
Tin	130	1.17
Titanium	> 0.83%	-
Thorium	5.6	0.0504
Toluene	-	-
Tungsten	101	0.909
Uranium	4.3	0.038

TABLE B-1. (Concluded)

Element/compound	Amount contained in refuse[1] (µg/g) (except as otherwise noted)	Kg/hr in feed (at 7.07 Mg/hr feed rate)
Vanadium	35	0.315
Vinyl Chloride	-	-
Ytterbium	2.8	0.025
Yttrium	19	0.171
Zinc	4,833	43.497
Zirconium	301	2.709

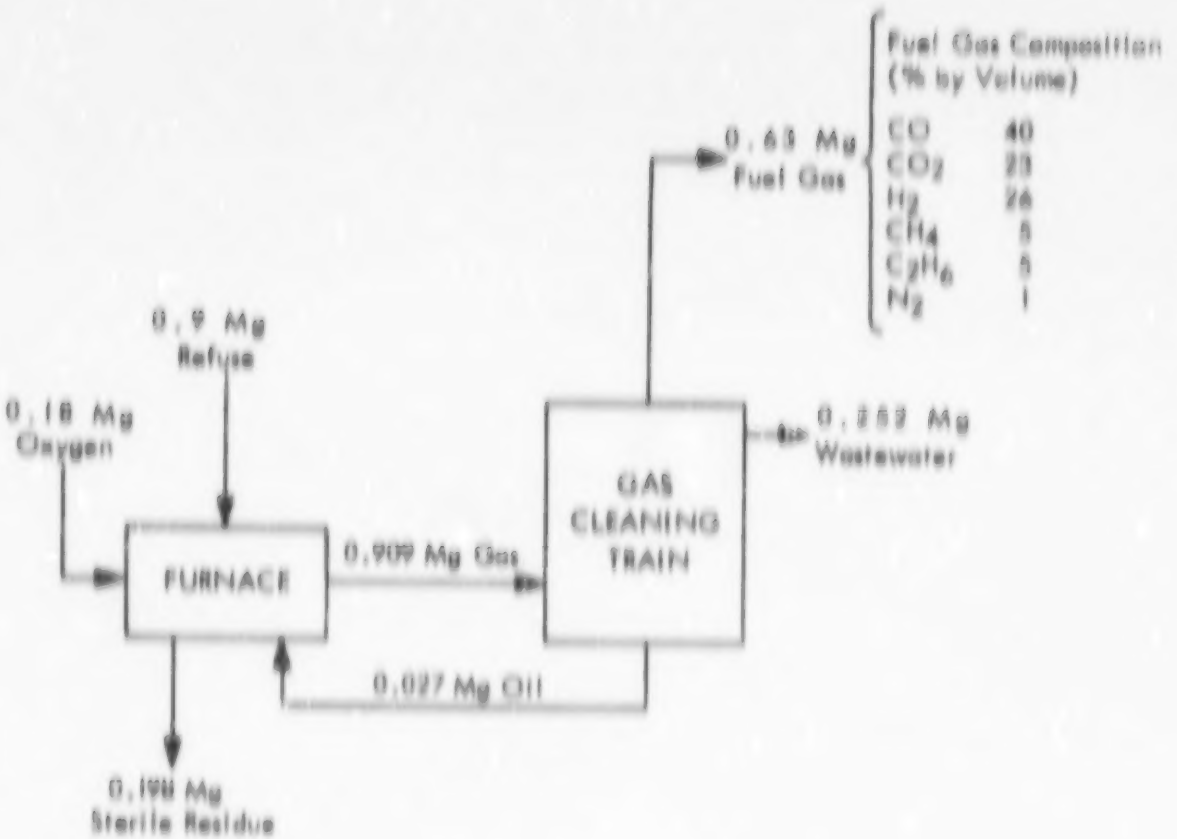

Figure 8-1. Purox system - typical inputs/outputs.

TABLE B-2: COMPUTATION OF FUEL GAS MOLECULAR WEIGHT

Fuel gas	% by volume	Mole per mole of fuel[a]	Molecular weights	Fuel gas molecular weight
CH_4	5	0.05	16	0.80
C_2H_6	3	0.03	30	1.10
H_2	26	0.26	2	0.52
CO	40	0.40	28	11.20
CO_2	23	0.23	44	10.12
N_2	1	0.014	28	0.28
		1.00	Total =	24.42

a Molecular weight of fuel = 24.42.

TABLE B-3: MOLE OF COMBUSTION PRODUCT PER MOLE OF FUEL

From	Combustion products: O_2	CO_2	H_2O	N_2
Fuel gas:				
CH_4	0.05 x 2 = 0.10	x 1 = 0.05	x 2 = 0.10	---
C_2H_6	0.05 x 3.5 = 0.175	x 2 = 0.10	x 3 = 0.15	---
H_2	0.26 x 0.5 = 0.13	-	x 1 = 0.26	---
CO	0.60 x 0.5 = 0.20	x 1 = 0.60	---	---
CO_2	0.23	--- 0.23	---	---
N_2	0.01	--- ---	---	0.01
O_2 from theoretical air	--- 0.605	---	---	---
N_2 from theoretical air	--- ---	---	---	0.605 x 79/21 = 2.278
Products at 0% excess air	---	0.78	0.51	2.289
30% excess air	0.1815	+ ---	+ ---	0.683
Products at 30% excess air	0.1815	0.78	0.51	2.969

TABLE B-4: COMPUTATION OF GAS VOLUME PER POUND OF FUEL GAS COMBUSTED

Item	Computation
total air supplied	= 0.787 x 100/21 = 3.748 mole
total dry products	= 0.1815 + 0.78 + 2.969 = 3.931 mole
$\frac{\text{dry flue gas}}{\text{lb fuel}}$ at 100°F, 14.7 psia	= $\frac{3.931 \times 555}{14.42}$ ft^3
	= 89.341 ft^3
Dry flue gas/0.9 kg of fuel	= 89.341 x 2,000 ft^3
Dry flue gas/0.9 kg of fuel	= 89.341 x 2,000 x 7 ft^3
	= 89.341 x 2,000 x 7 x 0.028317 m^3
	= 35,418 m^3

TABLE A-1. COMPARISON OF POLLUTANT CONCENTRATIONS WITH TLV OF POLLUTANT

Chemical compound	Concentration in flue gas (kg/m³)	Concentration with dilution of 1:200 (kg/m³)	TLV for chemical (kg/m³)	1/10 of TLV (kg/m³)	1/100 of TLV (kg/m³)
Acrylonitrile	—	—	—	—	—
Aldehyde/Acetaldehyde	—	—	—	—	—
Alkaline	—	—	—	—	—
Antimony	22.85	0.0011	0.5	0.05	0.005
Arsenic	5.642	0.0005	0.5	0.05	0.005
Asbestos	—	—	—	—	—
Barium	594.33	0.5	0.5	0.05	0.005
Beryllium	0.066	0.0000036	0.002	0.0002	0.00002
Bismuth	2.384	0.001	—	—	—
Boron	0.733	0.0037	—	—	—
Bromine	14.67	0.014	0.70	0.07	0.007
Cadmium	7.279	0.007	0.20	0.02	0.002
Calcium	—	—	5 (as CaO)	0.5	0.05
Cerium	17.1769	0.017	—	—	—
Cesium	0.689	0.00096	—	—	—
Chlorine	570.54	0.57	3	0.3	0.03
Chromium and compounds	551.85	0.55	0.5	0.05	0.005
Cobalt	84.61	0.084	0.1	0.01	0.001
Copper and compounds	735.248	0.735	0.1	0.01	0.001
Cyanides	—	—	5	0.5	0.05
DDT and metabolites	—	—	1	0.1	0.01
Dichloroethanone (acetic)	—	—	300	30	3
Dysprosium	1.256	0.001	—	—	—
Erbium	0.2295	0.00011	—	—	—
Europium	0.282	0.00032	—	—	—
Fluorides (F)	178.738	0.219	2.5	0.25	0.025

TABLE B-1. (Continued)

Chemical component	Concentration in flue gas (ng/m³)	Concentration with dilution of 1,000 (ng/m³)	TLV for element (ng/m³)	1/10 of TLV (ng/m³)	1/100 of TLV (ng/m³)
[illegible]	1,0700	0,005	—	—	—
[illegible]	0,16	0,0002	—	—	—
[illegible]	0,046	0,00006	—	—	—
Gold	—	—	—	—	—
Hafnium	1,300	0,001	0,5	0,05	0,005
Indium	—	—	0,2	0,02	0,002
Iridium (Iridium)	0,0230	0,00001	1	0,1	0,01
Iridium	—	—	—	—	—
Iron	—	—	1	0,1	0,01
Lanthanum	0,23	0,009	—	—	—
Lead	555,02	0,555	0,15	0,015	0,0015
Lithium	17,20	0,017	0,015 (hydride)	0,0015	0,00015
Lutecium	0,230	0,0002	—	—	—
Magnesium	—	—	10 (Mg++)	1	0,10
Manganese	198,20	0,198	5	0,5	0,05
Mercury	—	—	0,05	0,005	0,0005
Molybdenum	11,200	0,011	5 (sol. compd.)	0,5	0,05
Neodymium	3,840	0,003	—	—	—
Nickel	222,04	0,222	1	0,1	0,01
Niobium	3,840	0,003	—	—	—
Nitrogen oxides	—	—	9 (NO_2)	0,9	0,09
Osmium	—	—	—	—	—
Palladium	—	—	—	—	—
Phosphorus	—	—	0,2	0,02	0,002
Platinum metals	—	—	—	—	—
Plutonium	—	—	0,002	0,0002	0,00002
PCB	—	—	0,5	0,05	0,005
Praseodymium	1,46	0,001	—	—	—
Rhenium	—	—	—	—	—

TABLE B-5. (Concluded)

Element/compound	Concentration in flue gas ($\mu g/m^3$)	Concentration with dilution of 1,000 ($\mu g/m^3$)	TLV for element ($\mu g/m^3$)	1/10 of TLV ($\mu g/m^3$)	1/100 of TLV ($\mu g/m^3$)
Beryllium	—	—	0.1	0.01	0.001
Molybdenum	19,000	0.019	—	—	—
Nickel	—	—	—	—	—
Selenium	0.492	0.00049	—	—	—
Strontium	0.385	0.00038	—	—	—
Selenium and compounds	0.974	0.00097	0.2	0.02	0.002
Silicon	—	—	10	1	0.1
Silver	1.82	0.00018	0.01	0.001	0.0001
Sodium	—	—	—	—	—
Strontium	170.51	0.25	—	—	—
Sulfur	—	—	—	—	—
Tantalum	0.102	0.000102	5	0.5	0.05
Tellurium	—	—	0.1	0.01	0.001
Terbium	0.287	0.000218	—	—	—
Thallium	0.042	0.00004	0.1	0.01	0.001
Tin	33.33	0.033	2	0.2	0.02
Titanium	—	—	—	—	—
Tungsten	1.439	0.0014	—	—	—
Uranium	—	—	375	37.5	3.75
Vanadium	75.9	0.0759	1 (sol., fume)	0.1	0.01
Ytterbium	1.077	0.001	0.2	0.02	0.002
Yttrium	0.97	0.0008	0.5	0.05	0.005
Vinyl chloride	—	—	510	51	5.10
Zirconium	0.728	0.0007	—	—	—
Terbium	4.87	0.004	1	0.1	0.01
Zinc	1,179.6	1.179	1 ($ZnCl_2$)	0.1	0.01
Zirconium	77.69	0.077	5	0.5	0.05

TABLE 8-8. POLLUTANTS WHOSE CONCENTRATIONS IN FLUE GAS (AFTER DILUTION BY A FACTOR OF 1,000) EXCEED 1/10 AND 1/100 OF TLV[a]

Pollutants with concentration ≥ 1/10 TLV	Pollutants with concentration ≥ 1/100 TLV
Barium	Antimony
Chlorine	Barium
Chromium and compounds	Bromine
Cobalt	Cadmium
Copper and compounds	Chlorine
Lead	Chromium and compounds
Lithium	Cobalt
Nickel	Copper and compounds
Silver	Fluorides
Zinc	Lead
	Lithium
	Manganese
	Nickel
	Silver
	Tin
	Tungsten
	Vanadium
	Zinc
	Zirconium

a See Table 8-5.

The above approach is conservative and might include assumptions that may not be wholly applicable. (The use of the TLV as a measure of pollutant hazard is perhaps the most controversial assumption. However, it could serve as a framework in which pollutants can be rank-ordered according to their toxicity. [See Environmental Science & Technology, p. 256, March 1977.]) In the absence of measured data, the approach used could serve as a useful approximation to assess pollutant impacts. This type of approach can be particularly useful if it becomes necessary to focus on selected trace pollutants that are considered potentially hazardous.